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Heating & current drive efficiencies, TBR and RAMI considerations for DEMO

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HIGHLIGHTS

- New H&CD concepts with high wall-plug efficiencies are under investigation for DEMO.
- The present estimates regarding the impact on the TBR of the H&CD systems are promising.
- As initial target the maximum reduction of the TBR due to the integration of system sis $\triangle TBR \leq 0.08$.
- RAMI is considered from the beginning and proposals were made how to increase HCD system reliability.
- New proposal for clusters for EC and modular ion-sources for NB are made to improve DEMO reliability.

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ABSTRACT

The heating & current drive (H&CD) systems in a DEMOnstration fusion power plant are one of the major energy consumers. Due to its high demand in electrical energy the H&CD efficiency optimization is an important goal in the DEMO development.

The H&CD power for DEMO, based on physics scenarios for the different plasma phases, is needed for plasma initiation phases (incl. breakdown), current ramp-up, heating to H-mode, burn control, controlled current ramp-down, MHD control and other functions. Plasma control will need significant installed H&CD power, though not continuously used.

Previously, in the DEMO1 2015 baseline definitions, optimistic forecasted H&CD efficiencies had been assumed in the corresponding system code (i.e. PROCESS) module. Realizing that there is a high uncertainty in the assumptions the efficiencies have been modified and the impact on the DEMO power plant and basic tokamak configuration are discussed in this article.

A comparison of the various H&CD systems NBI (Neutral Beam Injection), Electron Cyclotron (EC), Ion Cyclotron (IC) in terms of impact on Tritium Breeding Ratio (TBR) due to various openings for the H&CD front end components in the breeding blanket (BB) is presented.

For increasing the reliability as major features the power per system unit and the redundancy are identified leading to a new proposal for clusters for EC and modular ion-sources for NB.

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1. Introduction

EUROfusion is undertaking a fusion energy research project, which is called DEMO, a DEMOnstration fusion power plant. DEMO shall deliver as first of its kind ~300–500 MW of electrical energy to the grid. The design has started in 2014 and is in a pre-conceptual design state. During this phase the teams develop different systems to unravel possible design choices and to find the best solutions and combine them to a DEMO which is Tritium self-sufficient and highly reliable.

A future fusion power plant DEMO is considered as a sustainable and more environmental friendly solution compared to any existing conventional power plant technology (e.g. fission, coal) in the world and is independent of natural fluctuations (like wind, solar).

To heat the plasma, extend the pulse time and provide various control functions three H&CD systems are developed for integration in DEMO, namely: Electron Cyclotron (EC) System, Neutral Beam Injection (NBI) System and Ion Cyclotron Range of Frequency (ICRF) System. The Workprogramme does not include Lower Hybrid waves. The DEMO H&CD mix shall be defined at about end of 2024, in the middle of the conceptual design phase.

The present baseline under development is DEMO1, a pulsed machine. As possible alternative a steady-state machine DEMO2 is under study with higher and more demanding physics and engineering assumptions.

2. Heating and current drive (H&CD) efficiencies

The efficiencies are discussed in detail in e.g. [1] and [2]. Both, the current drive & coupling (physics) and wall-plug (systems or transmission) efficiencies have impact to the DEMO design, especially for a steady-state device, in which the ohmic plasma current needs to be replaced completely by auxiliary CD power.

To move closer to a mature design it is proposed to use more realistic state-of-the-art systems efficiencies (ITER-like values; EC 35% and for NB 25%), this will lead with an assumed mix of 20 MW EC plus 30 MW NBI power during flat top to an average systems efficiency of 29%. This is a reduction of about 10% to former assumptions. These numbers will be updated based on new and validated findings and a minimum Technical Readiness Level (TRL) of the systems, ideally having been tested in a relevant environment.

For a pulsed machine (pulse duration >2 h) an efficiency reduction – as recently studied with PROCESS Code – of either the physics or transmission efficiency by 10% could in principle be compensated by increasing the fusion power/plasma volume and hence the major radius of the tokamak by ~0.1 m but with negative consequences on the overall machine costs.

The target of the work package (WP) H&CD is to carry out intensive R&D on wall-plug efficiencies and conduct studies on how to improve physics based efficiencies in collaboration with the Power Plant Physics & Technology (PPPT) department of EUROfusion (Table 1, Fig. 1).

The total amount of installed H&CD power of DEMO is mainly driven by the power needed for the H-mode access (LH-threshold) and the control during burn phase [3]. This field of activity is under precise evaluation.

The DEMO H-mode access during the plasma ramp-up was simulated with 'METIS', a fast tokamak simulator, and leads in view of uncertainties to 100–150MW_{inj} power applying the ITPA-Martin scaling [4].

Additional MHD control power for Neoclassical Tearing Modes (NTMs) of <10-15MW_{inj} is needed [5].

As long as the required total injected H&CD power is under study each H&CD system (EC, NBI, and ICRF) is developed aiming for ~50MW_{inj} power, knowing that the amount of installed power will be decided at a later state of the DEMO conceptual design (Table 1, Fig. 1).

3. Tritium breeding ratio (TBR) considerations for H&CD

As initial target the maximum reduction of the TBR due to the integration of auxiliary systems in the breeding blanket was defined as ΔTBR ≤ 0.08. This number is assumed to be equally shared) by (i) all H&CD systems & (ii) all Diagnostic systems. The value might be modified in the future depending on the local tritium breeding performance of the breeding blanket. The integration of the different H&CD systems into DEMO is currently studied by H&CD in collaboration with the Breeding Blanket project [7].

Some initial results and their TBR impact are discussed below.

3.1. EC launcher

The currently studied EC port plug design options are: (i) Blanket Integrated Design (plugged into the blanket) and (ii) Separated Blanked Module (SBM) (cf. Fig. 2). For the SBM two different arrangements of the launchers are under assessment, stacked 1 × 8 or 2 × 4 (rows x columns). The design depends also on the launcher technology with the focus on the Remote Steering Antennae (RSA)

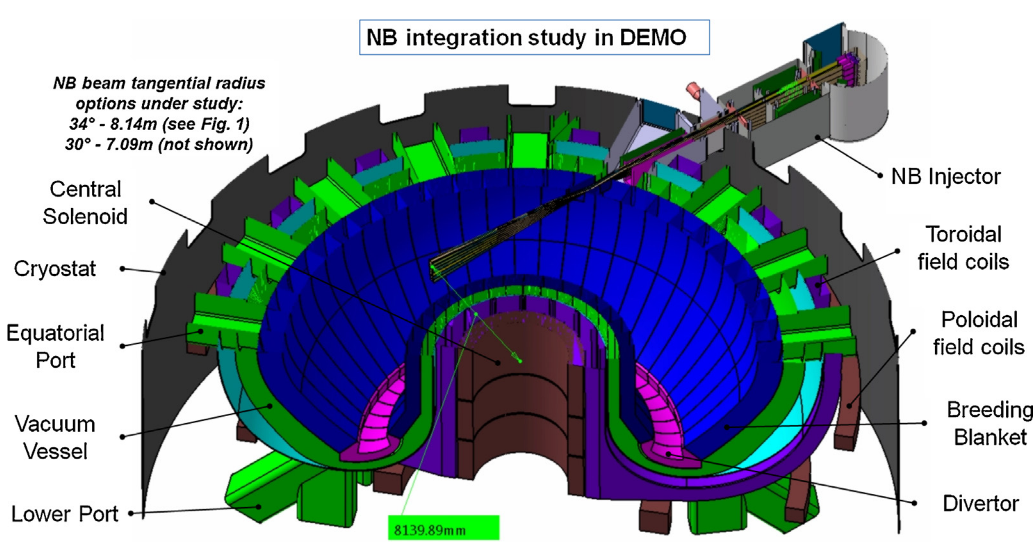

Fig. 1. Possible integration of the NBI in DEMO [6] (option with 34° injection angle).

Table 1
Main parameters of currently available (quasi off-the-shelf) ITER-like solutions versus new DEMO designs (one example of the most promising candidate solutions for the DEMO EC and NBI systems are shown below, some others are under development).

EC ITER	*EC DEMO (under study)*	*NBI ITER*	*NBI DEMO (under study)*
170 GHz gyrotrons	170/204 GHz gyrotrons	Single source (n = 1)	Modular sources (n = 20)
1 MW Efficiency 35% (system), (Gyrotron ∼50% + TL + MOU + Launcher + PS)	2 MW Efficiency ∼50% (system), (Gyrotron ∼60% + TL + MOU + Launcher + PS)	1000 keV, 17 MW Efficiency 25% (system) (Neutralizer ∼55%, stripping/halo 70%, etc.)	800 keV, 17 MW Efficiency ∼50% (system) (Neutralizer ∼70%, stripping/halo 90%, etc.)
Evacuated TL	Evacuated Quasi-optical TL	Gas-Neutralizer	Photo-Neutralizer
Front-steering antenna	Remote-steering antenna	Cryopumps	NEG pumps/Hg pump

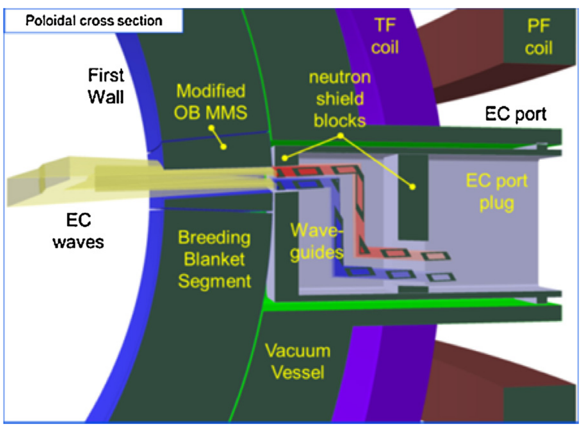

Fig. 2. EC conceptual launcher design example.

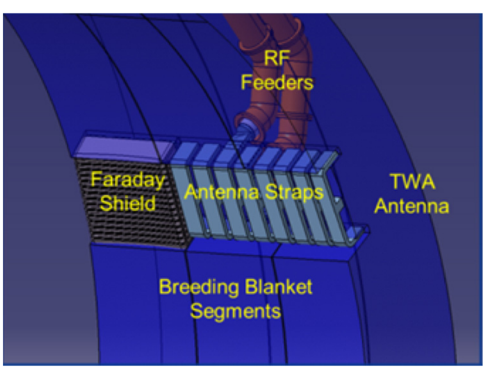

Fig. 3. ICRF 360° TWA antenna (1 of 18 sectors), RF feeding scheme still to be defined.

or alternatively on step-tunable gyrotrons (requiring Brewster windows), or a combination of both.

Neutronic calculations [8] result in ΔTBR of ∼0.0175 – ∼0.035 for 50MW_{inj} with power launched through 5 equatorial ports.

3.2. ICRF antenna

The ΔTBR of the ICRF travelling wave antenna (TWA) for DEMO (cf. Fig. 3) quantified in [9] has values of less than ∼0.006, depending on the blanket concept. The calculations were however done for the antenna only, neglecting the RF feeders.

Different feeding schemes (number and size of RF feeders) and related integration issues are under assessment. The feeding could be done (i) through the Central Outboard Segment (COBS) of the Breeding Blanket (BB), alternatively (ii) through both the Right and Left Outboard Segments (ROBS and LOBS) of the BB. For both alternatives a 1 line feeding or a 2 line feeding is actually considered.

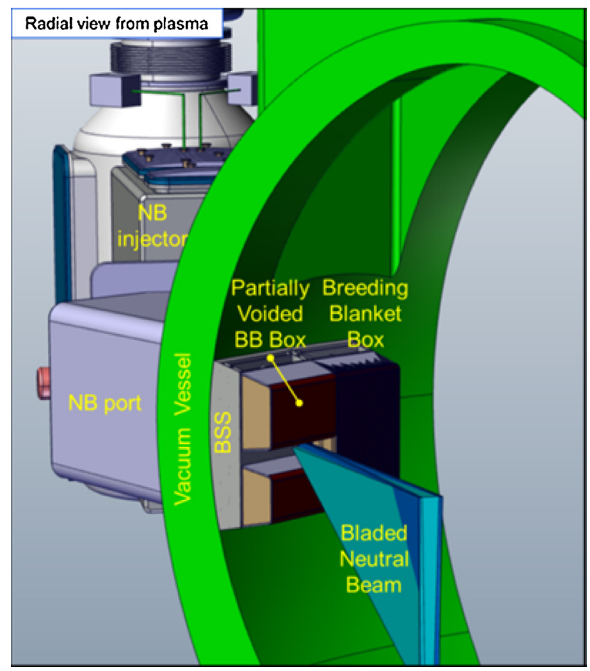

Fig. 4. NB blanket integration proposal.

The total number of feeders may vary between 36 (COB with 1 line feeding) up to 144 (ROBS and LOBS with 2 line feeding). The final ΔTBR of the TWA with RF feeders is not yet available and depends on which feeding configuration is chosen.

3.3. NBI duct

Depending on the integration strategy the ΔTBR is expected to be in the range of ∼0.002 to ∼0.006 for one NB injector. For the present assumption of 3 injectors (power launched from 3 inclined equatorial NB ports) and a partially voided port design (cf. Fig. 4), the NBI ΔTBR can be expected to be in the range of about 0.006–0.018 for 50MW_{inj}.

4. RAMI approach for H&CD

In a nuclear power plant environment maintenance periods are optimised. To ensure DEMO availability target are met, H&CD is applying from the concept stage RAMI methodology. The following tasks are proposed.

Firstly, define the interfaces of the H&CD. An example is shown in Table 2 based on the DEMO Plant Breakdown Structure (PBS).

Secondly, define the Functional Break Down Structure (FBS) of the H&CD with primary functions (cf. Table 3) and constraint func-

Table 2
Example of interfaces matrix.

DEMO PBS (partially)	EC	NB	IC
Magnet System	x	x	x
Vacuum Vessel	x	x	x
Divertor			
Thermal Shields			
Tritium Fuelling Vacuum (TFV)	x	x	x

Table 3
Example of H&CD primary functions.

Function N°	Functions
1	To control the fuel mix
1.1	To heat the fuel mix
1.1.1	To heat fuel mix to break down
1.1.2	To heat plasma to H mode
1.1.3	To heat plasma to burn
1.2	To drive the plasma current
...	....
2	To condition the wall

Table 4
Example of constraint functions.

Function N°	Interaction with PBS	Constraints function
n	Magnet System	To fit through magnetic coil system
n + 1	Vacuum Vessel	To maintain & control vacuum at the interface with plasma chamber

Table 5
Examples for aiming higher H&CD reliability.

EC System	*NBI System*	*ICRF System*
Clustered solution (cf. Fig. 6) to minimise the number of EC components	Increase number of sources (stacked 2 × 10 modular sources) instead of single source.	TWA as integrated part of the breeding blanket with the same reliability as the blanket.
Maximize the systems reliability, ~100% achieved after initial burn in	Decrease beam energy from 1 MeV (ITER) to 800 keV (DEMO)	Avoid antenna arcing due to lower power density (360° TWA)

tions (cf. Table 4). For each interface identified a minimum of one constraint function should be attributed.

Thirdly, attribute the primary functions to the H&CD system.

Fourthly, define at which machine state the system is performing the function.

The following steps will involve a further decomposition of the functions at the subsystem level followed by a Failure Mode Effects Analysis (FMEA). Having a clear understanding of the failure mode at an early concept stage is paramount to integrate, at minimum cost, the reliability, maintenance, monitoring and inspection requirements in the design. The FMEA was started to understand the failure modes before quantifying them. However these ratings are not yet finally settled and change is possible before the Failure Mode Effects and Criticality Analysis (FMECA) is implemented.

4.1. Examples of reliability studies for H&CD

At this stage of the project, knowing that the availability is a crucial factor for a DEMO operation, the RAMI work was focused first on the reliability, further studies will follow. New proposals to improve the reliability of the DEMO auxiliary heating systems are

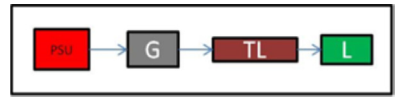

Fig. 5. Simple (ECL) Configuration.

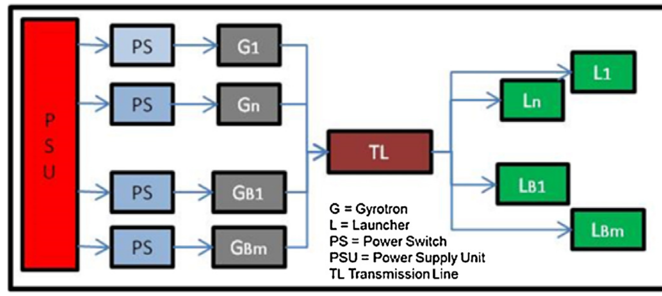

Fig. 6. Cluster EC Line (ECL) Configuration.

Table 6
Cluster ECL configuration with back-up items (marked bold).

n + m	Number of ECLs	R_{ECS}[a] (in %)	MTBF (in pulses)	Number of Gyrotrons
1 + **1**	28 + **1**	99,9601	2507	58
2 + **1**	14 + **1**	99,9896	9606	45
3 + **1**	10 + **1**	99,9945	18291	44
4 + **1**	7 + **1**	99,9972	35852	40
5 + **1**	6 + **1**	99,9979	47777	42
6 + **1**	5 + **1**	99,9985	66830	42
7 + **1**	4 + **1**	99,9987	79870	40
8 + **1**	4 + **1**	99,999	100198	45
9 + **1**	4 + **1**	99,999	100200	50

[a] Assuming lifetime after initial burn in and before end of lifetime cycle.

shown below (cf. Table 5) to give indications with a few examples about the type and direction of the strategy.

The clustered solution for the EC system (ECS) will be discussed in some more detail below. Fig. 5 shows first the principle of a simple Electron Cyclotron Line (ECL) which is commonly used in present day experiments.

A clustered ECL is shown in Fig. 6. and is composed of 1 to n components and B1 to Bm backup components.

For the case n = 1 (and without backup components m = 0) the ECL is – except the Power Switch (PS) – the same as in Fig. 5 with only 1 PSU (Power Supply Unit), 1 Gyrotron (G), 1 Transmission Line (TL) and 1 Launcher (L). For a higher number of EC lines (n > 1, m ≥ 1) the reliability R_{ECS} of the ECS increases whereas the number of items can be reduced as shown in Table 6.

The input values for the study are similar to ITER-assumptions (component R&D targets) [10], and supposed to have a reliability centred maintenance (RCM) approach for DEMO: G 98.0%, TL 99.9%, L 99.9%, PSU 100.0%.

Assuming a single redundancy (m = 1) (cf. Table 6) shows which reliability R_{ECS} and MTBF (Mean Time Between Failures) [11] could be achieved. The values reported are the result of an optimization process, aimed at identifying the minimum number of clusters to ensure a MTBF of >1000, which can be seen as 3 months of operation without faults. The best configuration can be found for 4 + 1 ECLs, in which the number of Gyrotrons is 40 (also for L and PS).

Former integration studies showed that one EC port plug is capable to collect max. 8 EC launchers (cf. chapter 3.1). Assuming the reliability targets are met the ECS will need 5 equatorial DEMO ports.

5. Summary

New H&CD concepts with high wall-plug efficiencies are under investigation. The present estimates regarding the impact on the TBR of the H&CD systems are promising. Detailed studies are ongoing hand-in-hand with the blanket integration. RAMI is considered from the beginning and proposals were made how to increase present reliability limitations.

Acknowledgments

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