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Innovative H&CD designs and the impact of their configurations on the performance of the EU DEMO fusion power plant reactor

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***Abstract*—Heating & Current Drive (H&CD) systems are being investigated for a demonstration fusion power plant DEMO to deliver net electricity for the grid around 2050 [1]. Compared to ITER, which has to show the generation of 500 MW thermal power, the target of DEMO is the successful production of 300 to 500 MW electrical power to the grid and to aim for a self-sufficient Tritium fuel cycle [2]. Three H&CD systems are under development for DEMO in Europe, the Electron Cyclotron (EC) System, the Neutral Beam Injection (NBI) System and the Ion Cyclotron (IC) System.**

Based on present studies [3] for plasma ramp-up, ramp-down and flat top phases, to be further validated in more detailed simulations, the assumed total launched power needed from the H&CD system in DEMO is in the range of 50-100 MW, to be provided for plasma heating and control.

The paper describes the designs and R&D status of H&CD systems considered for their deployment in DEMO in Europe and the impact of the H&CD configurations on their performances based on those areas described in the European fusion electricity roadmap [4] for the integrated design and system development.

The project also elaborates on innovative solutions to further increase the wall-plug efficiencies of H&CD systems based on more advanced concepts, with the target to reduce the recirculating power fraction in future fusion power plants. Different studies under investigation will be discussed such as, for NBI, the photo-neutralization and, for EC, noval concepts for gyrotron multi-stage depressed collector.

***Index Terms* — Fusion Power Plant, DEMO, Heating & Current Drive, Electron Cyclotron, Neutral Beam Injection, Ion Cyclotron, wall-plug efficiencies**

I. INTRODUCTION

In the course of the pre-conceptual design of the DEMOnstration fusion power plant several new and innovative DEMO H&CD systems and subsystem designs are under development. In this paper the impact of their configurations to the DEMO plant is described for some of the recently studied aspects. Evidence for this is exemplary given for the wall-plug efficiency as part of the technical specification of the H&CD systems. The efficiency will have a major impact on the internal recirculating power of the DEMO balance of plant [5] and assuming that the net electric power which DEMO is aiming to deliver to the grid by 2050 is around 300 to 500 MW a higher wall-plug efficiency can help to reduce the fusion power to be generated and also slightly decrease the major radius of the machine if the power exhaust to the divertor is assumed to be the same [6]. Therefore one major goal of DEMO H&CD system developments is to aim for high efficiency.

In the frame of the Power Plant Physics and Technology (PPPT) for the H&CD Research & Development (R&D) work and their (Pre-) Conceptual Designs [7] a number of studies were conducted to elaborate the applicability of innovative systems based on the experience gathered so far from ITER conceptual design and R&D and some of the most relevant recent design assessments for the DEMO H&CD are described in this paper. Since the studies are comprehensive and done by several groups the results are updated and exchanged among the teams on a regular basis.

In the following chapters a first overview of these studies will be summarized, and more details are given in the various references attached to each paragraph.

II. DEMO ADVANCED NEUTRAL BEAM (NB) CONFIGURATION TO PERFORMANCE STUDIES

For the DEMO NBI system two approaches are considered: a conventional NB system with beam neutralization on gas

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target (ITER-like system) [8], and a more challenging NB system based on beam photo-neutralization [9],[10] which if feasible would offer a huge benefit of much higher neutralization efficiency compared to state-of-the-art technology, i.e. gas neutralizers. Knowing the related risks and challenges for this development and the tight timeline and development costs for mock-ups it was decided to invest in such innovative concept because it also offers great advantages. The requirements to be satisfied are quite different especially for the optical parts, which are new for an NB injector as e.g. optical tables, high precision optical cavities [11],[12] of high finess with highly reflective mirrors and extremely high power lasers, which are at the leading technological edge. The attempt was started with a development to integrate such a system and is under studies at reduced scale to highlight the different issues and estimate the concept feasibility.

In order to integrate such system detailed studies for the most important issues related to a fusion power plant are on-going, these are in particular (i) port integration studies especially focusing on the required breeding blanket system openings, (ii) the heat load estimates on components like NB liners and the plasma facing components within the duct, (iii) the assessment of duct pump options to reduce the re-ionization losses, (iv) the finding of feasible remote handling schemes and (v) the conduction of neutronics studies to simulate the neutron flux and fluences and shut-down dose rates to estimate the amount of radiation after plasma operation during repair, thus achieving by proper material selection, sufficient shielding and design, e.g. by dog-leg structures and minimization of gaps.

A. NBI conceptual design

The NB systems were compared below (Table I) for two options, an ITER-like NB [8], an advanced DEMO-NB [9], [10] and a model used in previous simulations called ´METIS Ref.´(cf. [13], [14]). The ITER-like NB injector is characterized by a high extracted current density and a high beam voltage, but both were found to be contradictory for a highly reliable power plant operation over a long operation period. Also the use of only one NB source has possible drawbacks in terms of reliability and it is more difficult to construct in terms of high thermal loads on the grids and their thermal expansion. The fact that if one or even more of their Radio Frequency (RF) driver fails the whole injector is out of operation lead to an alternative modular approach for DEMO. Therefore, the DEMO advanced concept has several RF sources, and if one of the drivers would fail, the whole injector would be still operable losing only a limited amount of the nominal injected power. Also a new concept of RF ion source is under study with Helicon plasma drivers, and the first results are encouraging [15], [16].

The extracted current density of the DEMO advanced injector was balanced to a lower value in order to have the possibility to reduce the filling gas pressure in the ion source, with a consequent reduction of beam stripping losses through the accelerator. Moreover, the beam energy was decreased by 20% to improve the reliability of the whole system regarding voltage holding, as this aspect was identified as one of the most critical issues. Because of higher efficiencies one of the DEMO advanced injectors is still able to produce sufficient amount of power so that with the same number of injectors, i.e. three, the total injected power of 50 MW can be achieved. This thanks also to the application of laser-neutralizers presently under development, whereby first proof-of-principle experiments show promising results.

TABLE I
NB INJECTOR OPTIONS (MAIN PARAMETERS)

NB injector parameter	ITER-like	DEMO advanced	METIS Ref.*
Extracted Current Density [A/m^2]	286	200	-
Number of sub-sources	1	20	1
Tangency radius [mm]	7090 (30°)	7090 (30°)	8000
Beam voltage [kV]	1000	800	1000
Power per injector [MW]	16.5	16.8	25
Number of injectors	3	3	2
Injector wall-plug efficiency [%]	26	51	-
Total Injected power from NB system [MW]	49.5	50.4	50.0

** "METIS Ref." is the beam used in all the work done so far within WPPMI (a work group under PPPT) with METIS system code. It has been set to fit the desired scenario computed by PROCESS code (a DEMO reactor simulation code), but it does not correspond to any NB system design.*

The arrangement of the NB injectors is shown in Fig. 1. The beams are placed in the north of the tokamak for the reason that the main power supply unit building is actually planned to be there as for ITER (cf. Fig. 9).

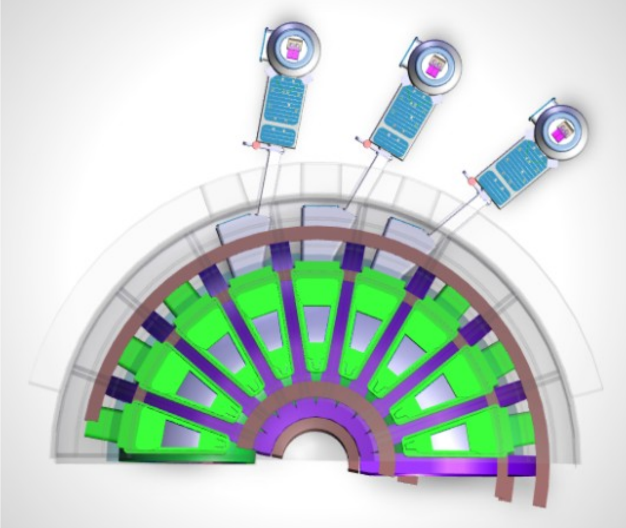


Fig. 1. EU DEMO1 2015 with 3 NB injectors as viewed from the top

In contrast to ITER, it is foreseen to have an inclined part of the NB port for the liner and dedicated port duct pumps and a bigger radial part for maintenance access.

B. NBI physics simulations

Based on the parameters given by the PPPT for the DEMO1 pulsed scenario such as temperature and density profiles (cf.

Fig. 2, left) the beam-plasma interaction was studied with the fast tokamak simulator METIS [14]. For this purpose it was considered the plasma alpha particle heating for the burning plasma (with limited fusion gain factor of Q = 40) and a NBI heating only (the EC heating was set to zero) (cf. Fig. 2, right).

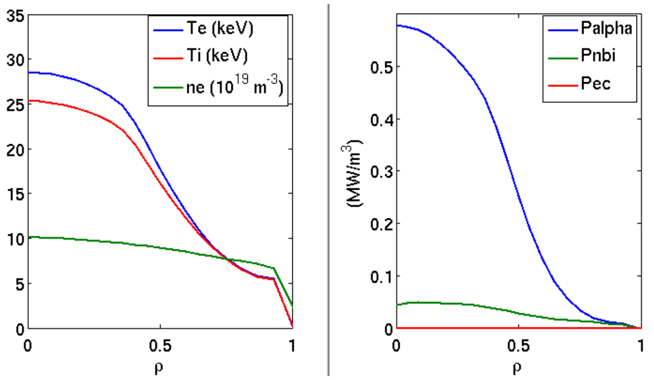
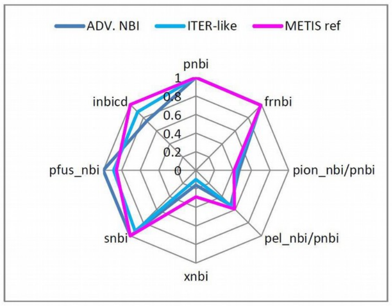


Fig. 2. NB simulations in METIS, plots for Ti, Te, ne (left) and Palpha, Pnbi, Pec (right)

The simulations were compared for different parameters, see Fig. 3, in which the NBI power (pnbi) for all three studied system options were kept at 50 MW. The fraction of absorbed power in the plasma is always ~100% since the fast ion losses result negligible. The fusion power (pfus_nbi) coming from NBI-plasma interaction is only slightly affected and this results from the beam trajectory (xnbi) differences. The overall plasma is not much influenced by these changes, although the NB power deposition, induced current, etc. are different. The NB rotation part (snbi) in Fig. 3 is given not in absolute but only relative values. At the moment, since the ´natural´ rotation of the plasma is not known, the impact of the NB rotation cannot be estimated and will be part of future studies. The driven current by auxiliary HCD NBI power is higher for the high energy beams (1 MeV) compared to the DEMO advanced (800 keV) version. For a pulsed DEMO machine this is of minor importance, whereas for a steady state machine indeed, it would have a huge impact on the machine design and performance.



pnbi	NBI power (W), relative comparison (1=max(pnbi))
frnbi	fraction of NBI absorbed in the plasma (1=100% absorption)
pion_nbi	NBI power going on ions (W)
pel_nbi	NBI power going on electron (W)
xnbi	NBI maximum position (ρ)
snbi	rotation torque due to NBI (N m), relative comparison (1=max(snbi))
pfus_nbi	NBI induce D-T fusion power of alpha (W), relative comparison (1=max(pfus_nbi))
inbicd	NBI current drive (A), relative comparison (1=max(inbicd))

Fig. 3. Radar chart of the ITER-like NB vs. DEMO advanced concept

The values gained in Fig. 3 with METIS calculations were later refined with other (BBNBI and ASCOT) codes.

With this physics based comparison it was concluded that the advanced NBI does not show major deviations compared to the ITER-like solution and the further implementation to DEMO is favorable and recommendable [13].

In the following study the integration of the beam was performed with different (in total 3) options [9] of which two are described in Fig. 4 below. The two shown options are different in injection angle. The comparison was required in order to see the drawbacks of the one or other solution.

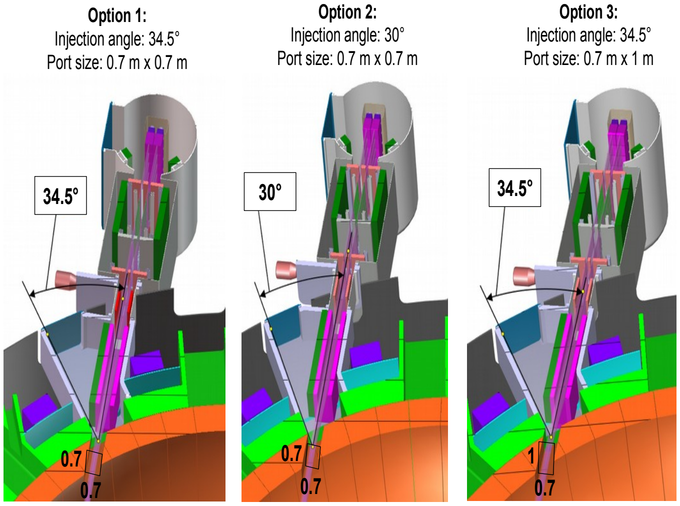
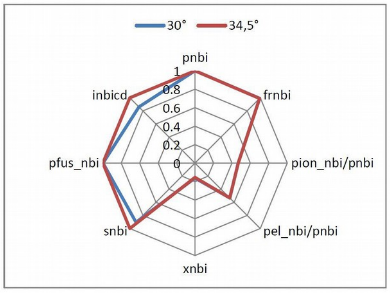


Fig. 4. Options for injection angles and integration studies shown without bioshield (opt. 2 was selected for further studies)

A physics comparison was done with METIS for both options as shown in Fig. 4 and the result can be seen in Fig. 5. It shows that independently of the tangential angle (30° vs. 34.5°) the NBI performance is similar, except for the reactions of the fast ions with the plasma (which represents only 1% of the total fusion power and is therefore negligible) and for the current drive, which for a pulsed DEMO is - as explained before - of minor interest.



pnbi	NBI power (W), relative comparison (1=max(pnbi))
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pion_nbi	NBI power going on ions (W)
pel_nbi	NBI power going on electron (W)
xnbi	NBI maximum position (ρ)
snbi	rotation torque due to NBI (N m), relative comparison (1=max(snbi))
pfus_nbi	NBI induce D-T fusion power of alpha (W), relative comparison (1=max(pfus_nbi))
inbicd	NBI current drive (A), relative comparison (1=max(inbicd))

Fig. 5. Radar chart of the NB Option 1 compared to the Option 2

Finally Fig. 6 shows a viewgraph for the studies of the shine-through losses to the opposite wall (through the plasma), which were found for both options as negligible. The simulations done with the codes BBNBI and ASCOT are explained in [13].

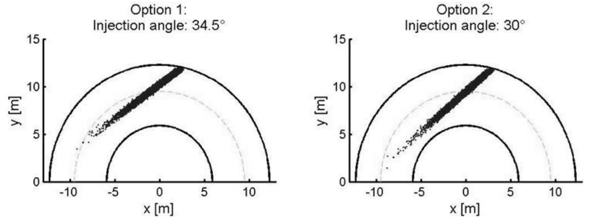


Fig. 6. Shine-through studies of the 2 NB options

For the ramp-up phase presently studies are on-going to find the right timing at which the NBI can be switched on during the ramp-up phase to avoid too high shine-through losses. This is very likely only at the end of the plasma ramp-up phase possible for the NB with 800 keV beam energy. Indeed a lower NB energy, the injection trajectory which does not intersect the inner wall and the large DEMO volume would permit an earlier switch on of the beam. If this combined low and high beam energy scenario is not applicable for DEMO this consequently requires another H&CD system (like EC) to form a dense enough plasma which allows the high energy beam NBI to inject power to assist the L-H transition heating.

C. NBI neutronics studies

For the two NBI options as shown before Monte-Carlo N-Particle (MCNP) studies were also performed to allow the estimation of the neutron fluxes and fluences, the displacements per atom (dpa) in the materials and to assess the material lifetimes. Furthermore the shut-down dose rate after operation was computed. The results for the neutron streaming analysis are shown in Fig. 7.

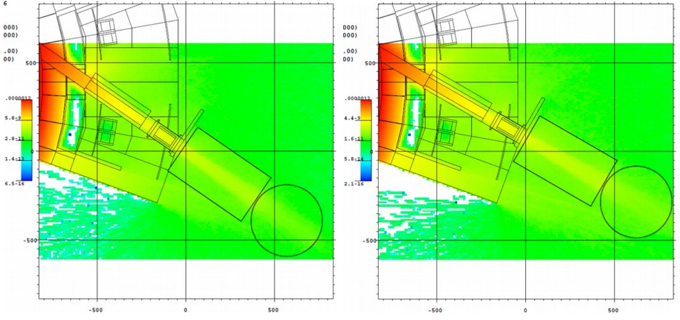


Fig. 7. Neutron streaming analysis NBI option 1 (left) & 2 (right side)

The immediate conclusion from the two pictures is that both injector options behave similar, and to see the difference better, a superposition of the both results was made and the differences are seen then in Fig. 8. These MCNP studies led to two other results, not shown here, which are, that the liner materials dpa´s are within the limits given for the lifetime of this material in DEMO and that the Toroidal Field (TF) coil heating slightly exceeds the limits so that for some parts of the NB port additional shielding needs to be added. The studies are on-going.

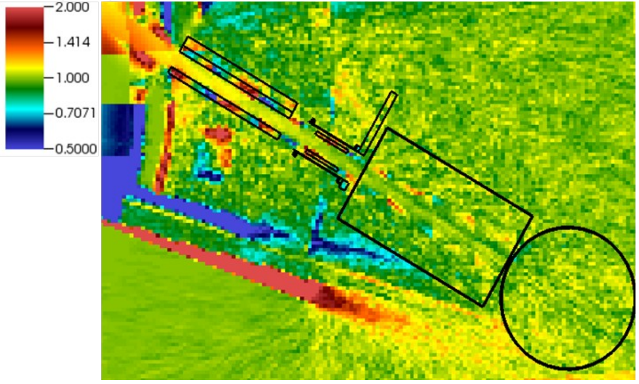


Fig. 8. Neutron streaming comparison option 2 / option 1

Legend: range from 0.5 (dark blue) to 2.0 (violet red) is the ratio of neutron flux of option 2 to option 1

III. Electron Cyclotron (EC) Configurations for Definition of DEMO (Plant) Layout

A similar approach was done for the EC system. A number of physics studies (not discussed here) were conducted together with conceptual layout studies [17],[18]. Also different options for the configurations were investigated [19].

A. EC plant layout

Two different EC plant layouts were studied. The first EC plant layout proposal is to locate three gyrotron (RF) buildings at 120° around the tokamak and the second plant layout in which the EC power sources are allocated in only one building in the south of the tokamak according is shown in draft plant layout, see Fig. 9. In both cases a minimum distance between tokamak and gyrotron building(s) has to be considered as described below. The connections from the EC launchers to the EC power sources (gyrotrons) in DEMO (as in Wendelstein 7-X, Greifswald, Germany) are planned by Quasi-optical (QO) Transmission Lines (TLs) in beam tunnel(s). In contrast to W7-X, where dry air is the transmission media, in DEMO the EC beams are transmitted in vacuum for Tritium safety considerations and because of higher power densities. A preliminary conceptual design of the Evacuated Quasi-optical (EQO) TL based on mirror (Fig. 10) confocal layout can be found in [17]. The final design might have about 25% more outer diameter to further reduce the EC transmission losses.

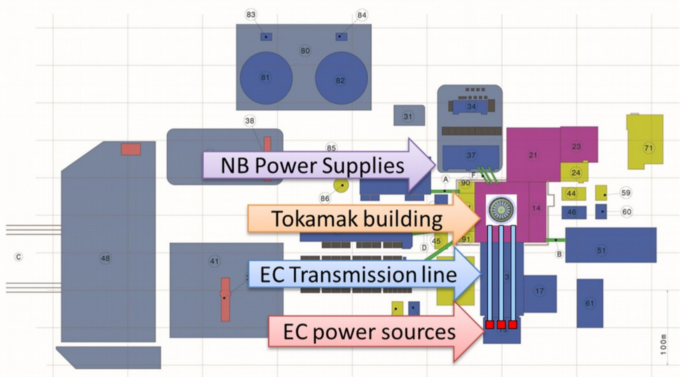


Fig. 9. Provisional DEMO plant layout with EC and NB systems (other EC configurations were also, as described in the text before)

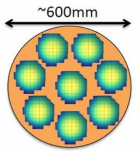


Fig. 10. Sketch of the minimum envelope circular surface of the Evacuated Quasi-optical (EQO) Transmission Line (TL) to host 8 individual beams (total ~600 mm diameter, tbc.: +25% in diameter to reduce losses)

The minimum length of the TL is depending also on the stray magnetic field of the tokamak as the EC gyrotrons operation is limited by the stray magnetic field. In order to find a position for the gyrotrons compatible with their operations a magnetic field map was computed (Fig. 11).

- Gyrotron requirements (G = Gauss):

$B_R < 2$ G (radial), $B_Z < 10$ G (axial)

- Gyrotron hall requirements/achievements:
  $B_R < 2$ G, $2 \text{ G} < B_Z < 5$ G
- Torus-Gyrotron distance as simulated (cf. Fig. 11)
  DEMO >120 m (for comparison in ITER is 105 – 135 m)

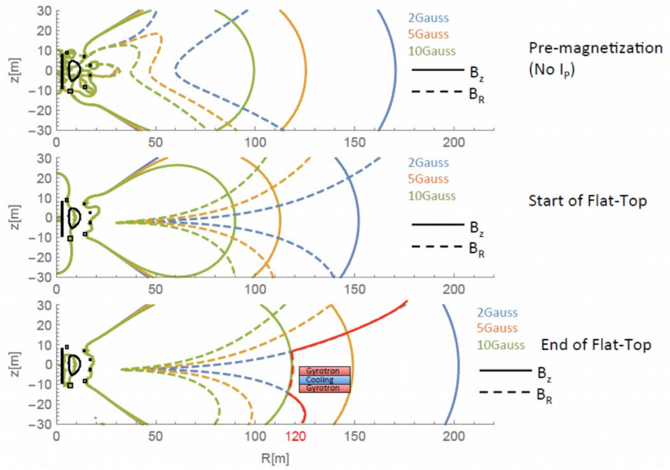
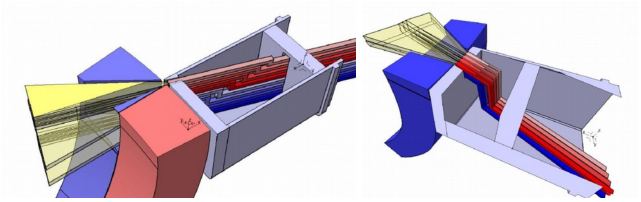


Fig. 11. DEMO stray magnetic field map for radial and axial field

B. EC launcher configurations

Two type (out of some others) of possible DEMO EC port plug configurations were studied in more detail, both which stop behind the blanket and for which the blanket has funnel type openings to cope with the beam stearing of about +/-15° (cf. Fig. 12).



Configuration A: a stack of 8 antennas

Configuration B: a stack of 2 rows of 4 antennas

Fig. 12. EC equatorial port plug options (isometric view)

MCNP calculations were performed for both port plug options. First results show that the neutron shielding is not sufficient especially for the configuration A and further improvements are foreseen before the study will be repeated for an improved design. Solutions are envisaged to be feasible by dog-leg structures and including more neutron shield blocks in empty spaces. A different configuration with the aim to reduce the impact due to neutron streaming and foreseeing an integrated blanket design of the port plug with the blanket system will also be considered.

C. EC remote steering antenna

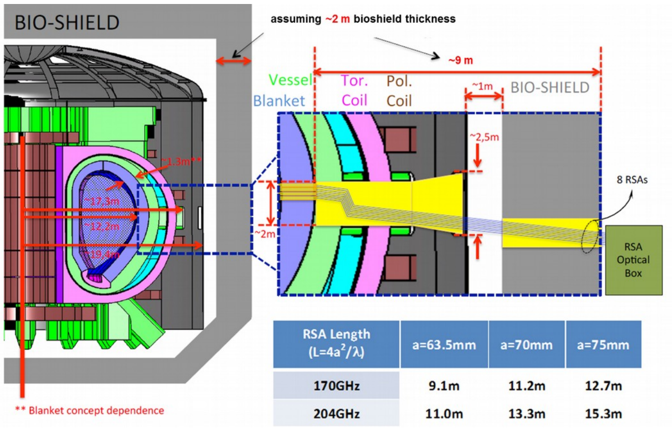
The big advantage of the remote-steering concept as in DEMO applied compared to a front-steering mechanism as in ITER is that no movable plasma facing parts exist. The following characteristic points need to be considered for the DEMO design:

- In-Vessel Waveguides (WGs) implemented in equatorial port plugs with dog-leg structures.
- In-Vessel WGs at the back-end connected to the Remote Steering Antenna (RSA) mechanisms.
- RSA antennae connected to Evacuated Quasi-optical Transmission Lines (EQO TLs) in underground duct up to the RF building.
- Neutron shield blocks can be inserted around the WGs to protect overheating in Toroidal Field (TF) coils and vacuum vessel (VV).

As for the EC port plug also different design options were foreseen for the Remote Steering Antenna (RSA) (cf. Fig. 13).

The following specific points are to be considered for the RSA (pre-) conceptual design studies:

- The optimized length is depending on frequency and cross-section of the RSA and important in order to place the RSA optical box outside the bioshield.
- The RSA are connected to diamond windows (Tritium and vacuum barrier) installed between RSA optical boxes and EC EQO TLs.
- RSA and diamond windows shall be well accessible in the EC port cell outside the bioshield.



RSA Length ($L=4a^2/\lambda$)	a=63.5mm	a=70mm	a=75mm
170GHz	9.1m	11.2m	12.7m
204GHz	11.0m	13.3m	15.3m

Fig. 13. Remote Steering Antenna (RSA) design options

The table in Fig. 13 shows the lengths of the RSA for different waveguide sizes ´a´ and for two possible DEMO gyrotron frequencies 170 GHz and 204 GHz. The lengths vary from 9.1 m to 15.3 m. The bioshield thickness is assumed to be about ~2 m and with this the distance from the antenna opening at the plasma side to the outer bioshield radius, where the RSA box is situated, needs to be >9 m. According to the calculated antenna lengths the integration of all waveguide options as shown in Fig. 13 can be approved to be feasible.

D. EC gyrotron coaxial-cavity technology and multi stage depressed collector concept

In future the coaxial-cavity gyrotron technology shall help to achieve multi-megawatt, multi-purpose and, at the same time, frequency step-tunable gyrotrons operating at an output power significantly above 1 MW and an operating frequency up to 240 GHz. For example, new cooling technologies and advanced key components, such as an innovative invers Magnetron Injection Gun (MIG) are under development to achieve that goal [20].

To recuperate the kinetic energy from the spent electron beam and, hence, to increase the total efficiency of gyrotrons, the single stage depressed collector (SDC) design approach is so far the only applicable solution. It is implemented in all recent gyrotrons, e.g. for Wendelstein 7-X, Greifswald, Germany and it will be implemented for ITER gyrotrons. The today's efficiency of fusion gyrotrons is around 50%. The target for DEMO is a total efficiency of the gyrotrons of better than 60%. It is possible to achieve by the development of multi-stage depressed collector concepts.

A novel solution is the ***E***×***B*** drift design [21],[22], in which an effective energy sorting of the electrons becomes feasible and the secondary electrons can be handled. Various design ideas were discussed and a two stage design looks as most promising (cf. Fig. 14).

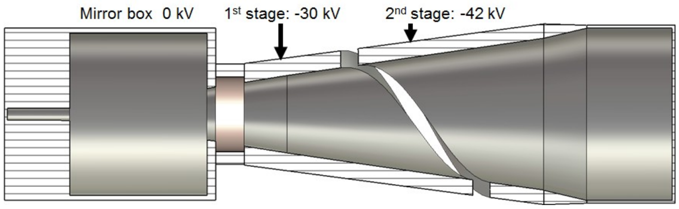


Fig. 14. Two-Stage Gyrotron Collector based on E×B

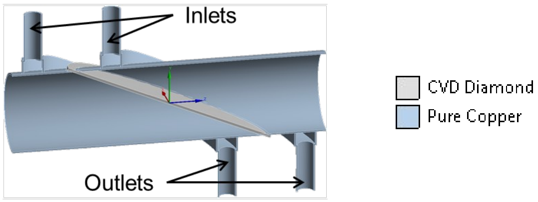
The achievable collector efficiency of this innovative concept might exceed 75% and the resulting total gyrotron efficiencies based on this concept might reach >60%. Further studies are required and a proof-of-principle is in the long term planned to confirm the validity of the concept.

E. EC diamond windows

The present conventional single chemical vapor deposition (CVD)-diamond disc is for a fixed frequency operation foreseen for 50 mm / 63.5 mm inner diameter WGs. The discs are available and in use. Brewster angle windows for 63.5 mm WGs are challenging and currently the manufacturing feasibility is under investigation.

The large Brewster angle windows are required in combination with the use of step tunable high power gyrotrons to allow frequency sweeping and to cope with power >1 MW.

The power performances of large synthetic diamond windows were studied first for the 50 mm inner diameter WGs (cf. Fig. 15 top).



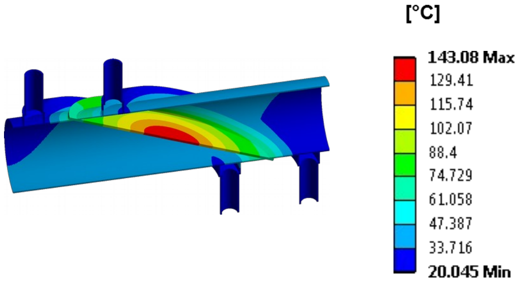


Fig. 15. Power performance of large synthetic diamond windows (Example of FEM analysis result)

The temperature distribution is indicating stresses in the diamond windows which lead to the fact that a pre-stress treatment under manufacturing becomes necessary. An example for the temperature distribution is shown in Fig. 15 bottom [23].

Different options for the manufacturing of large diamond windows are under investigation (e.g. direct large window fabrication). Depending on the successful production of these large synthetic CVD windows, requiring low losses (tan δ) and good homogeneity, other related systems might become available for DEMO, such as the before mentioned frequency tunable gyrotrons and truncated waveguide launchers. The following Table II summarizes some details of the DEMO window design options.

TABLE II
SUMMARY OF THE DEMO DIAMOND DISC OPTIONS

	DEMO Option 1 Single Disc Window	DEMO Option 2 Brewster Angle Window
angle of installation	0° (to the beam propagation direction)	67.2°
diameter / size	Ø 80 mm for 63.5 mm WGs	180 mm x 96 mm (elliptic) disc for 63.5 mm WGs
gyrotron type	Multi-frequency	Frequency tunable

IV. ION CYCLOTRON (IC) DISTRIBUTED ANTENNA

The distributed IC antenna is a new concept for DEMO and described e.g. in [24]. Several options are under investigation and the antenna design is presently under studies [25]. Further investigations will be undertaken and can only be discussed at a later stage of the project after consolidation and further studies on physics, integration, antenna strap and Faraday Shield (FS) design and the corresponding layout of the Transmission Lines (TLs). With the different design options Tritium breeding ratio (TBR) calculations shall be carried out in due time due in order to see the impact of the different TLs schemes. Available remote handling schemes and the TL and antenna integration in the breeding blanket are another prerequisite and therefore more in depth integration studies have to be carried out.

V. CONCLUSION

The work undertaken for the studies of the novel and innovative designs of H&CD systems and subsystems and their impact on other systems and interfaces e.g. with breeding blanket, vacuum vessel or buildings and also on the whole plant layout, i.e. recirculating power, electrical energy demand, power released to the plasma but also on the space occupied in port cells by e.g. remote steering antenna were discussed. Intensive studies were done in the area of physics for IC, EC and NB plasma interaction, magnetic stray radiation and neutronics calculations were done. Depending on the results of further R&D especially on the Brewster windows manufacturing the implementation of frequency step tunable gyrotrons might be applicable to DEMO. The focus is given to efficiency improvements in NB and EC systems and ways to it by photo-neutralization or E×B staged depressed collector designs are promising and first results are available.

The scoping studies were undertaken on most promising design options after discussion in the design teams of H&CD work package but also by interdisciplinary work with the teams of the other work packages, mainly Breeding Blanket (BB), Tritium, Fueling and Vacuum (TFV), Heat Transfer, Balance of Plant and Site (BoP), Materials (MAT), Safety (SAE) and Remote Maintenance (RM). Other work packages will be involved for the H&CD work at a later stage.

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