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Conceptual Design of the DEMO EC-System: Main Developments and R&D Achievements

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Abstract. For the development of a DEMOnstration Fusion Power Plant the design of auxiliary heating systems is a key activity in order to achieve controlled burning plasma. The present heating mix considers Electron Cyclotron Resonance Heating (ECRH), Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Heating (ICRH) with a target power to the plasma of about 50 MW for each system. The main tasks assigned to the EC system are plasma breakdown and assisted startup, heating to L-H transition and plasma current ramp up to burn, MHD stability control and assistance in plasma current ramp down. The consequent requirements are used for the conceptual design of the EC system, from the RF source to the launcher, with an extensive R&D program focused on relevant technologies to be developed. **Gyrotron**: the R&D and Advanced Developments on EC RF sources are targeting for gyrotrons operating at 240 GHz, considered as optimum EC Current Drive frequency in case of higher magnetic field than for the 2015 DEMO1 baseline. Multi-purpose (multi-frequency) and frequency step-tunable gyrotrons are under investigation to increase the flexibility of the system. The principle feasibility of a 236 GHz, 1 MW CW conventional-cavity and, alternatively, of a 238 GHz, 2 MW CW coaxial-cavity gyrotron are under investigation together with the development of a synthetic diamond Brewster-angle window technology. Advanced developments are ongoing in the field of multi-stage depressed collector technologies. **Transmission Line (TL)**: Different TL options are under investigation and a preliminary study of an evacuated quasi-optical multiple-beam TL, considered for a hybrid solution, is presented and discussed in terms of layout, dimensions and theoretical losses. **Launcher**: Remote Steering Antennas has been considered as a possible launcher solution especially under the constraints to avoid movable mirrors close to the plasma. With dedicated beam tracing calculations, the deposition locations coverage and the wave absorption efficiency have been investigated, considering a selection of frequencies, injection angles and launching points. An option for the **EC system** structure is proposed in clusters, in order to allow the necessary redundancy and flexibility to guarantee the required EC power in the different phases of the plasma pulse. Number and composition of the clusters are analysed to have high availability and therefore maximum reliability with a minimum number of components.

1. Introduction

For the development of a DEMOnstration Fusion Power Plant, the design of auxiliary heating systems is a key activity in order to achieve controlled burning plasma. At present the considered heating systems [1] are Electron Cyclotron (EC), Neutral Beam Injection (NBI) [2] and Ion Cyclotron (IC) [3] heating with a design target power to the plasma of about 50 MW for each system. Present simulations of various scenarios together with extrapolation from present tokamaks generation have been used to define the main tasks assigned to EC system design, which must be assured during the entire pulse. These requirements are used as inputs for the conceptual design of EC system, from the RF source to the launcher, with an extensive R&D program focusing on relevant technologies not yet available and to be developed in view of DEMO. The main physical tasks are listed in the Table 1 collecting what has been used in the performed simulations of the possible scenarios [4], [5], [6]. The described design is based on the pulsed EU DEMO1 2015 [7], where Electron Cyclotron Current Drive (ECCD) does not have a major role for pulse sustainment, but essentially for Neoclassical Tearing Mode (NTM) control during plasma flat top. The total powers for Ramp up and Ramp down, calculated in [1,4], are larger and the value of 50 MW in the Table 1 assumed that the whole design value for ECW (50 MW) will be affected to these functions In the meantime the EU DEMO1 2015 project is not yet definitely fixed, as a great effort in scenario modelling is still on going. For these reasons we selected two possible frequencies as reference, to be able to perform the basic calculations for a conceptual design of the DEMO EC System: 170 GHz for heating and 204 GHz for current drive tasks. The final choice will be done once the DEMO design phase will be completed.

Table 1. *Main DEMO EC tasks with corresponding power required and deposition location, assuming the design value of 50 MW.For all these functions, a reliability of 100% is expected.*

Task	Power [MW]	Localization [ρ]	Mode
Assisted Breakdown	6-10	< 0.3	Heating
Ramp up and L-H transition	50	< 0.3	Heating/CD
Main heating	50	< 0.3	Heating/CD
Sawtooth control	2	0.3	CD
NTM control (q=2; q=3/2)	10-15	0.85; 0.75	CD
Ramp down	40	0.3 - 0.5	Heating

2. Gyrotron R&D and Advanced Developments

The present EC conceptual design focuses on the EU DEMO1 2015 baseline for a pulsed machine with aspect ratio AR = 3.1 and B_T = 5.7 T. Assuming maximum compatibility with ITER the heating frequency will be at 170 GHz. Taking into account a moderate upshift factor of 1.2, the corresponding optimum Electron Cyclotron Current Drive (ECCD) frequency will be 204 GHz. While the EC conceptual design is following this new baseline for a pulsed machine, the gyrotron R&D and Advanced Developments are focusing on a possible operation up to 240 GHz, originally considered as a compromise between the optimum ECCD frequency for the 2012 DEMO1 baseline and a considerably major step for high frequency, high power (2 MW) gyrotron. Hence, the continuation of this target is anticipating the possible long term options for a steady state DEMO (EU DEMO2 2015), with EC operation at higher toroidal fields, with plasma parameters and launching angles requiring frequencies significantly above 200 GHz. Additionally, "multi-purpose (multi-frequency)" and "frequency step-tunable" operations are under investigation. "Multi-purpose" operation is targeting for possible RF output frequencies corresponding to multiples of the half-wavelength of the single-disc RF diamond window (~34 GHz steps for a window thickness of ~1.85 mm) allowing EC operation at different magnetic field configurations (slowly-varying) and at different discrete frequencies for heating and current drive (e.g. 136/170/204/238 GHz). "Frequency step-tunability" is targeting for the fast stepping (in seconds) of the operating frequency. Steps of 2 – 3 GHz shall be possible using a broadband RF output window technology. That will allow the fine tuning of the deposition location. Most important in the realization of the Chemical Vapor Deposition (CVD) diamond-disc Brewster-angle window technology is, firstly, to find a proper solution for the production of large diamond-disc windows, secondly, to realize suitable assembly technologies for merging the diamond-disc window with the copper cuff, and, thirdly, to achieve a sufficient cooling during operation. Finally, in the project, it is considered to push the total efficiency of gyrotrons to above 60% by using multi-stage depressed collectors (MSDC). Different MSDC concepts are under investigation.

Two different concepts are under investigation to check the principle feasibility for a 2 MW gyrotron operating at 240 GHz. Those are the conventional-cavity technology, and, alternatively, the EU coaxial-cavity technology [8].

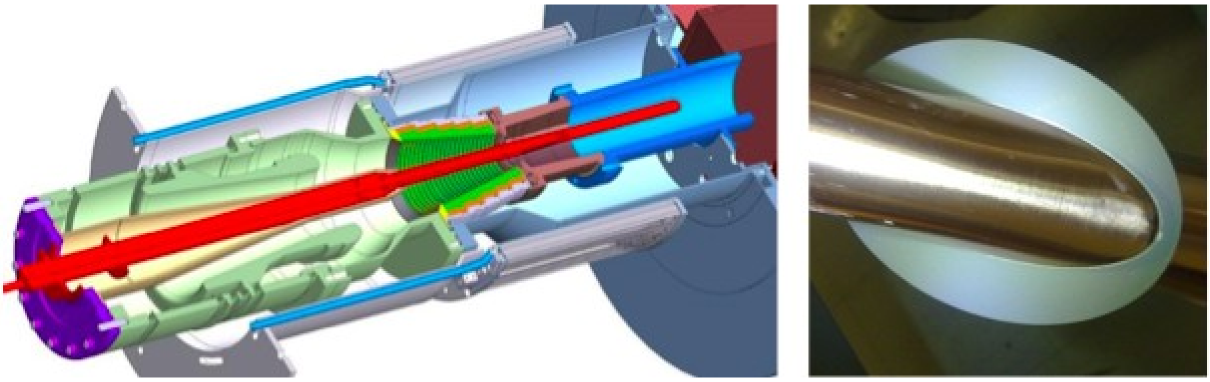

Figure 1 Left: Implementation of the insert into a coaxial-cavity gyrotron. Right: CVD-diamond disc mounted into a circular waveguide (diameter: 50 mm) at the Brewster-angle of 67.2°.

The Figure 1 (left) is showing the relevant part of a coaxial-cavity design. The coaxial insert is colored in red. The ongoing research is focusing on the maximum achievable output power and efficiency versus operating stability. Physical and technical restrictions considered in the designs are: a spread of the electron guiding centers $\leq \lambda/5$; an emitter current density ≤ 4 A/cm²; an ohmic loading on the cavity wall ≤ 2 kW/cm². In [9] a generic mode selection strategy for highly overmoded multi-frequency gyrotrons with a quasi-optical output coupler and a CVD diamond single-disc window is presented in a very general form. The strategy bases on an expedient rating scheme for different series of operating modes. It is shown that a simple relation can be derived which provides a proper indication whether a certain mode lies within a multi-frequency suitable series. Based on these considerations, one finds that a coaxial-cavity three-frequency gyrotron with the $TE_{49,29}$-mode at 237.5 GHz is expected to retain sufficiently low internal losses if operated at the allied modes $TE_{42,25}$ at 203.6 GHz and $TE_{35,31}$ at 170.0 GHz. From the simulation an output power of about 2MW seems to be possible. One of the most important challenges of the coaxial-cavity design is that the coaxial-insert might be slightly misaligned with respect to the cavity wall, due to manufacturing tolerances. Depending on how large this misalignment actually is, it will lead to a drop in interaction efficiency, mode purity and/or mode stability, and thus in output power and reliability. Since gyrotrons are welded and evacuated after assembly, one might be unable to fully compensate such an internal misalignment after bake-out in case it turns out to be critical. Therefore, one needs to define misalignment tolerances based on realistic simulations beforehand. In [10, 11] possible effects of the insert misalignment on the electron beam and the electromagnetic modes, and how to treat those effects numerically in interaction simulations are shown. The theoretical considerations are supported by experimental campaigns to verify the superior performance of the coaxial-cavity technology [12, 13]. In [14] the further development of a longer-pulse 2 MW 170GHz gyrotron is shown which includes an advanced water cooling system for the beam tunnel, cavity and launcher. The main target of the project is to achieve a pulse length of 1s and the conservation of the modularity of the gyrotron. Therefore, an independent water cycle of each gyrotron component is designed and verified with the multi-physics software COMSOL.

With regards to the conventional-cavity technology a generalized, systematic cavity design approach has been proposed and implemented for a $TE_{43,15}$-mode cavity at 236GHz (see [15]). Based on this, optimum operating parameters of the gyrotron are shown. Using the EURICIDE code [16], a time-domain self-consistent simulation has been performed to verify the interaction performance. In total, 99 competing modes have been taken into account. Stable RF output of about 920kW has been achieved with an interaction efficiency of 36%. With the suggested mode series, multi-frequency operation of the DEMO gyrotron has been estimated at 170 GHz / 203GHz / 236GHz and 269GHz. In [17] the possibility for fast frequency step-tunability in leaps of 2 – 3GHz steps is presented for the 236 GHz conventional-cavity gyrotron. The selection of modes for the frequency-tunable gyrotron is restricted by the requirements that they should have large coupling, suitable frequencies, and their caustic radius should be nearly identical in order to have the same quasi-optical launcher design for all the selected modes. Efficient MW-level operation within the ±10GHz frequency range is demonstrated for the selected modes. The simulation results support very high conversion efficiency for all selected modes with the designed hybrid-type launcher. Here, it has to be considered that the gyrotron operating frequency primarily depends on the operating magnetic field. The time required to move from one frequency to its neighboring one is governed by the rate of change in the cavity magnetic field, hence, it is limited by the tuning capability of the superconducting (SC) magnet. So far, it is estimated that it will be possible to do a frequency step in the range of seconds.

Apart from an advanced fast-switching SC magnet, a broadband output window is necessary for a frequency-tunable gyrotron. The transmission properties of a conventional single-disc window allow gyrotrons only to have operating frequencies at $f_N=(c/(2\cdot d\cdot\sqrt{(\varepsilon_r)})\cdot N = f_1\cdot N)$ within an ±1 GHz frequency range. Here, d is the window thickness, ε_r is the relative permittivity of the synthetic diamond material and N is an integer number. For a standard RF window thickness (ranging from 1.50mm to 2.25mm typically) of a CVD-diamond disc ($\varepsilon_r = 5.67$), the corresponding fundamental frequency (f_1) ranges from ~30 GHz to 40 GHz, which does not support step-frequency tunability [18]. The Brewster-angle window, which has a wide transmission band is a favorable option to achieve the frequency step-frequency tunability. Figure 1 (right) shows a Brewster angle window mounted into a circular waveguide of 50mm diameter; the Brewster-angle window is 67.2°.

A first successful implementation into a megawatt-class D-band (111.6 GHz - 165,7 GHz) short-pulse prototype gyrotron operating at 10 different frequency steps and related results from experiments at short pulses (ms) have been reported in [19, 20]. The fundamental issue in the Brewster-angle technology is the production of a diamond disc with a sufficiently large axis. Ideally, a typical gyrotron window would require an aperture of 80mm. That results in the need for a diamond disc with a minimum large diameter of 220mm. Today, a manufacturing technology to produce such large diamond discs does not exist. Within the EUROfusion project it was thus decided to, firstly, set a more realistic target for this project.. Hence, a waveguide with an aperture of 63.5mm is considered. As possible future production technology the joining of a mosaic disc is under investigation. The joining itself might be performed joining the disc parts together by a localized CVD diamond growth process.

Beside an output power of 1-2MW, to minimize the recirculating power, output efficiencies above 60% are required for a future DEMO. Single-stage depressed collectors will allow a maximum efficiency of the recuperation of maximum 60%. Assuming an electronic efficiency of 35% for the gyrotron interaction, the total efficiency is limited to ~50%. Hence MSDCs are mandatorily required for future fusion gyrotrons. Different concepts for multi-stage depressed collectors (MSDC) are under investigation. Three major items will have to be overcome: the large spread of the kinetic energy of the electrons after the gyrotron interaction; the large transversal energy of the electrons and the large axial magnetic field of the SC magnet at the gyrotron collector. First approaches for MSDCs, which can be found in the literature, have not been successful. [21-24]. Major reason is the generation of secondary electrons, which deteriorate the performance of the gyrotron. Another very promising approach has been published in [25]. This second concept uses the E×B drift to sort and drift electrons towards the electrodes according to their initial velocities. In order to apply the proposed design approach to conventional gyrotrons, the transformation of the cylindrical hollow electron beam to one or more sheet beams is proposed using appropriate electrostatic and magnetostatic fields. A conceptual design for a MSDC system based on that idea is proposed in [26] which results in a collector efficiency of about 86%.

3. EC System Conceptual Design

The conceptual design of the EC system is based on subsystems performances chosen to fulfil the tasks reported in Table 1 together with the constrains typical of a reactor producing electricity, as it is DEMO. The ideal required overall reliability to deliver 50MW with EC system is 100 % and can be obtained using redundancy and subsystems with high enough singular reliability. The system will be based therefore on a strong modularity and on the possibility to substitute each failing subunit with one in standby. The basic architecture is a *cluster* of 8 sources (gyrotrons) fed by only one high voltage power supply for the cathode current and one anode power supply for each gyrotron. The 8 microwave beams are transmitted by single multi-beam line (considered an unique subsystem, even if composed by separate waveguides) and delivered to a single launcher composed by 8 independent antennas hosted in one port. An exception can be considered for the *cluster* dedicated to NTM stabilization that feeds two different launchers (4 beams each) potentially located in two different (vertical) ports. Using this modularity the system reliability has been calculated, assuming 98% of reliability for the gyrotron, 99.9 % for the transmission line and 99.9% for the launcher. As figure of merit we use the Mean Time Between Failures (MTBF) that must be as high as possible. 1000 pulses between two (major) faults of EC system lead to 2000h for the MTBF, being 2h the DEMO pulse length, which is equivalent to 99.9% of reliability The analysis [27] allowed select the proper optimized number of element of each cluster (8) and the total number of cluster: 4+1 for main tasks and one for NTM stabilization.. In this scheme one line in each operating cluster is in stand-by and one whole cluster is also in stand-by, ready to substitute a faulty cluster. Based on this analysis, to insure >99.9% reliability, the total number of 2MW gyrotrons considered in the system is therefore 40, 28 of them in operation to deliver 50MW to the plasma, assuming 10% of losses in the transmission of the power.

Source: we consider a gyrotron capable to operate at (two) different frequencies (170GHz and 204GHz) with the same power level (2MW), same efficiency (60%), Gaussian output content (98%) and reliability (98%). These numbers are general requirements that we assume technologically mature at DEMO construction, even not already possible for the present generation of the tubes developed for ITER. The two frequencies will be used to fulfil pure Heating task (170GHz) or to produce the CD (204GHz) required for special needed, as NTM stabilization. For CD we have assumed an upshift factor of 1.2 and the possibility to use the same diamond window, this lead to a step of 34GHz between the two operating modes. A second option is based on a frequency step-tunable gyrotrons, capable to operate in steps of about 2 to 3GHz over a 10 to 12 GHz bandwidth in order to deposit power at different resonating fields. This option can be useful if the launcher cannot direct the power in the required positions. The step tunable gyrotron will be used in association with a broadband RF output window (e.g. Brewster-angle window) described in the previous paragraph on R&D activities.

Transmission Line (TL): On present experimental fusion devices two solutions for TL with a high power handling capability are adopted: Evacuated corrugated waveguide (EWG) (DIII-D, TCV) and Quasi-Optical (QO) in air as used for W7-X. These two options are under consideration starting from a preliminary study of an evacuated quasi-optical (EQO) multiple-beam TL, that can be considered for a hybrid (EWG+EQO line) solution containing the benefits of both. The main DEMO TL requirements are: target efficiency of 90%, power handling of 2MW CW, multi-frequency (or broadband) capability and tritium compatibility; moreover it has to be considered that in DEMO the number of installed line will be relevant (around 40 as will be discussed later under system reliability requirements). A Multi-Beam TL (MBTL) could be a compact arrangement capable to reduce the complexity of the system and to save space and components provided that the distance is not excessive. As power transmission in air is not compatible with tritium segregation requirements (in case of failure in the torus window) we imagine a MBTL enclosed in a vacuum vessel. The reference design is based on mirror confocal layout with single units composed by a two mirrors forming a dogleg used for line bends and for straight path (see Figure 2). One pumping system is foreseen for each unit. The characteristic length of the system L is defined as the distance between the two focusing mirrors.

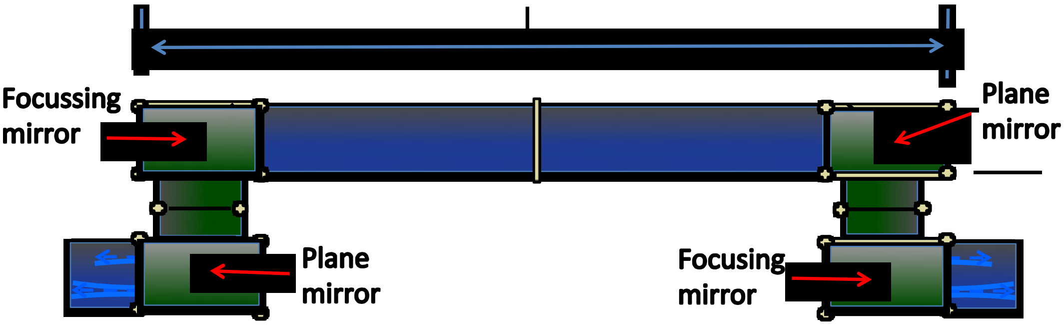

Figure 2: Sketch of the Evacuated Quasi-Optical section

In order to validate this solution a preliminary analysis has been conducted. The theoretical absorbed power density on a mirror surface is function of L, being the diameter of mirror depending from relative distance. Considering 8 Gaussian beams, 2 MW each arranged on vertices of a regular heptagon with the eighth in the center, we obtained <0.6 MW/m^2 for $L > 5/6.5$m and <0.4 MW/m^2 for $L > 10/11$m with an envelope radius of each beam of 0.2/0.24m. An overall estimation of losses has been carried out on the basis of [28], and using two possible lengths (100 m and 150 m) and $L = 8$m. The transmission efficiency at 170 GHz is 91% and 88% respectively, close to the initial requirement of 90%. From a preliminary cost analysis carried out considering only mirrors, vacuum envelope and pumping system, based on recent quotations, we found that the cost per meter is related to L and tends to be constant for $L > 6$m and comparable with the EWG option.

Antennas: DEMO EC launching system is a launcher with a sufficient flexibility and without movable parts in the proximity of plasma. Remote Steering Antenna (RSA) or simple truncated waveguides, in conjunction with step tunable gyrotron, are candidates for such a launcher. An extensive engineering effort to integrate the antennas into the tokamak is presently carried on and reported in [30]. Two concepts are under assessment: a Blanket Separated Design (BSD), where the port plug stops behind the Outboard Multi-Module Segment (OB-MMS) and a Blanket Integrated Design (BID), where the port plug penetrates the OB-MMS up to the plasma. A general assessment, based on EU DEMO 2015 baseline design and on beam tracing code TORBEAM [29], has been performed to evaluate launching performance and plasma accessibility from a RSA located in different points situated in a poloidal section and scanning different frequencies (from 140GHz to 230GHz). For each frequency the steering angle has been varied (±15°) in order to reach the different radial position. The plane of steering has been also chosen to exploit the widest range of possibilities. Results in terms of deposition location accessibility ρ and driven current I_{CD} are shown in Fig. 2 (left) when a beam (170 GHz) is launched from an equatorial port plug point (EPP3, R=13.545 m and Z=0 m) with toroidal and poloidal injection angles in the range β=[0°, 30°] and α=[-30°, 30°] respectively. Fig. 2 (right) shows the results for the same launching point EPP3 when different frequencies are considered. The largest plasma coverage is obtained with lower frequency at the expense of a reduction of a factor 2 in CD efficiency. As the requirement for NTM stabilization is ECCD with high efficiency up to ρ=0.85 it is necessary explore the possibility of higher poloidally launching points with different steering plane orientations at high enough frequency.

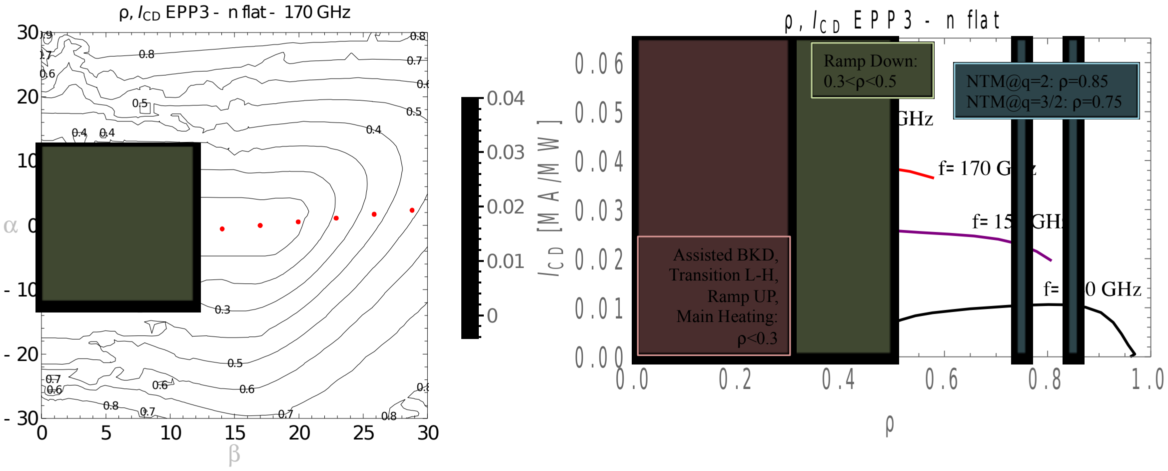

Figure 3 Left: contour plots (black curves) for normalized deposition location ρ and total driven current I_{CD} (color code, MA/MW) as a function of the injection angles (α, β) as determined by a given steering plane (red dots). The case of 170 GHz frequency is shown, with launch point EPP3. Right: summary of total driven current I_{CD} (MA/MW) as a function of accessible deposition location ρ with the beam launched from EPP3 with $\alpha_0 = -10°$, $\beta_0 = 17°$ for frequency in the range [140 to 200 GHz]. Required EC functions are shown with rectangular areas.

A preliminary estimation of the minimum apertures required by the launchers on the Breeding Blanket (BB) has been done in order to allow a first evaluation of the impact on TBR of the EC launchers. Calculations [30, 31] results in ΔTBR of ~0.0175 to ~0.035 for 50MWinj with power launched through 5 equatorial ports.

Conclusion

The status of activities on EC DEMO system in the framework of Work Package Heating and Current Drive under the umbrella of EUROfusion consortium are presented and discussed. The activities in the frame of gyrotron R&D and Advanced Developments (up to 240GHz, 2MW RF output power, >60% efficiency, multi-purpose and step-frequency tunable operation) are considered strategically necessary in order to prepare mature technology not only for the pulsed DEMO1 but also for the steady state DEMO2 device. Major parts in the research are focusing on the coaxial-cavity gyrotron technology, manufacturing and implementation of large CVD diamond-disc Brewster-angle windows and multi-stage depressed collector technologies.

A conceptual design of EC system starting on the physical requirements for DEMO1 and on the constrains for a nuclear power plant is also presented. An architecture based on 5 identical clusters of 8 gyrotrons connected by with a multi-beam transmission line to 8 singular remote steering antennas is discussed and motivated on the basis of technical requirements and RAMI consideration.

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