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Design specifications for the ion cyclotron heating amplifier system in the Divertor Tokamak Test facility

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ABSTRACT

This paper provides an overview of the basis of design of the high-power amplification for the Ion Cyclotron Heating system of the Divertor Tokamak Test facility. Notably, this system will be entirely based, for the first time, on solid-state technology, marking a significant milestone in the development of advanced fusion energy systems. The amplifier operates within a frequency range of 60–90 MHz, delivering MW-level power and supporting long pulse durations. The design specifications of amplifiers under different operating conditions, such as plasma experiments, wall cleaning, and conditioning are provided. By explaining the reasons behind the adoption of solid-state amplifiers, the paper highlights the role of solid-state technology in advancing fusion research.

1. Introduction

The Divertor Tokamak Test facility (DTT) is a superconducting device with a D-shaped design, currently planned for construction at the ENEA Research Center in Frascati, Italy. Its primary objective is to address the critical challenges related to controlled power and particle exhaust, thereby contributing valuable insights to forthcoming fusion experiments, such as ITER and DEMO. DTT is characterized by key parameters including a magnetic field strength of $B_0 = 6$ T, plasma current $I_p = 5.5$ MA, major radius $R_0 = 2.19$ m, and minor radius $a = 0.7$ m. It is specifically designed to be a highly adaptable tokamak, enabling the exploration of different magnetic configurations. Furthermore, the device is engineered for high reliability and operational availability, with a target of 100 operational days per year. DTT will require approximately 45 MW of auxiliary heating, delivered through a combination of electron cyclotron resonance heating (ECRH), ion cyclotron resonance heating (ICRH), and neutral beam injection (NBI) [1].

The ICRH is a well-established technique used for plasma heating in fusion devices [2–6]. In the DTT, the ICRH system is primarily intended for heating bulk ions, facilitating H-mode access, and wall conditioning, with a allocated power of 6 MW in the reference configuration, potentially increasing to 9 MW based on initial system results. The preferred ICRH scheme involves heating minority species such as ^{3}He or H, which aligns with the mission objectives of DTT. The system is modular in design, with each module comprising four transmitters and two antennas. Following recent design optimizations, the ICRH system has been upgraded [7,8], with grid tube technology being replaced by solid-state technology. This makes DTT the first tokamak to implement solid-state amplification throughout all stages of its ICRH system. In this paper, Section 2 will provide an overview of the state-of-the-art in solid-state technology, while Section 3 will present the studies that led to defining the specifications for the DTT transmitters and the current amplifier design. Finally, Section 4 will offer a comparison between solid-state technology and grid tube technology in the context of DTT, followed by conclusions.

2. Emerging role of solid-state amplifiers in scientific research

Solid-state (SS) technology [9] is increasingly replacing vacuum tubes across various large-scale scientific facilities, with the field of accelerators being one of the most prominent sectors to have already adopted this advancement [10–14]. This transition has been driven by the advantageous characteristics of SS systems: in particular, these benefits include greater reliability, modularity and availability, as well as the elimination of high voltage requirements. The modularity of

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solid-state amplifiers enables flexible design configurations, improving both reliability and ease of maintenance. Additionally, solid-state amplifiers offer fault tolerance of a few transistors, allowing for continued operation despite minor component failures. In contrast to traditional systems, where component failure could disrupt entire operations, solid-state systems allow for individual module replacements without downtime, thus increasing overall system uptime and efficiency. Other key benefits include reduced phase noise, longer operational lifetimes, shorter warm-up times, and easier maintenance. Thanks to these advantages, solid-state technology is not only widely used in accelerators but is also being considered for broader applications, especially in fusion machines.

In the fusion energy field, efforts are already underway to integrate solid-state technology into various systems [15–17]. One of the primary challenges is managing high-power systems efficiently under extreme conditions. Solid-state technology shows great promise in addressing these challenges, particularly for ICRH systems [18], where current designs are already compatible with the power (MW) and frequency demands (MHz) .

Currently, the efforts made in the field of ICRH are focused on designing a single amplification stage based on solid-state technology, as can be seen in [19–21]. In line with the trend toward solid-state technology, DTT has commissioned the development of its amplification system, which will be entirely based on solid-state amplifiers.

3. Key specifications of DTT solid state trasmitters

This section outlines the research that contributed to defining the technical specifications for DTT transmitters. These studies have determined the optimal operational frequency ranges and stability parameters of the system, with each specification adapted to meet the specific needs of DTT applications.

3.1. Scenarios study and frequency range definition

The specification of DTT transmitters was guided by investigation of various heating scenarios, with a particular emphasis on ^{3}He and H minority heating cases. To support this analysis, a series of parametric studies were conducted adopting the TOMCAT 1D full-wave kinetic wave equation code [22], incorporating temperature profiles, magnetic field strengths, and plasma density distributions in Deuterium plasmas, as detailed in [23]. The cases analyzed corresponds to a full-field configuration with $B_0 = 5.84$ T, $T_{0e} = 18$ keV, and $T_{0i} = 9.9$ keV. Figs. 1 and 2 illustrate the results of parametric studies detailing the single pass fraction of power absorbed per 1 W of power delivered by the radiating structure, as a function of both frequency and the concentration of the minority species. In the same plot, the red line represents the resonance frequency of the ion species for safety factor q = 1.

Studies have identified optimal frequency ranges to effectively address minority heating scenarios. In particular, the absorption peaks for H are found to lie between 70 and 90 MHz, while for ^{3}He, the range is between 50 and 60 MHz, based on TOMCAT simulations. However, further analysis of the precise positioning of the resonance peaks shows that this frequency range is slightly narrower. For example, 50 MHz is not feasible due to the peripheral location of the absorption peak. Consequently, 60 MHz has been selected as the lowest frequency, as it provides central deposition and represents a good trade-off between ion absorption and resonance peak positioning. A system with a fractional bandwidth of 57% entails significant technical challenges, for example complicating to a large extent the design of combiners like 3 dB hybrid couplers. Moreover, with a shorter frequency range, another operational and experimental advantage of SS technology over tetrodes and their cavities can be easily exploited: the design of a broadband amplifier that maintains a relatively flat power response, with negligible variation across the operational frequency range. For

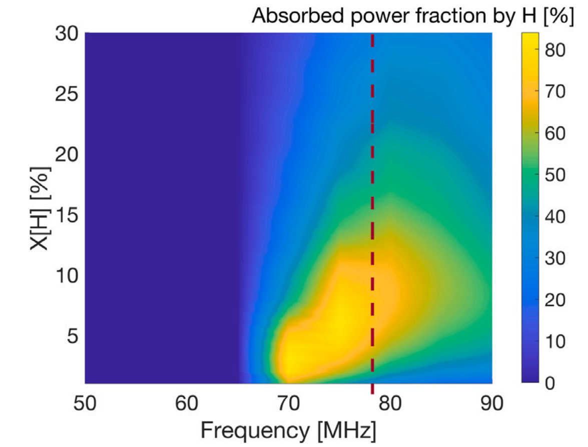

Fig. 1. Single pass absorption of H minority in D plasma as a function of the H concentration and frequency, as computed by the TOMCAT code for toroidal mode number $n_{tor} = 25$.

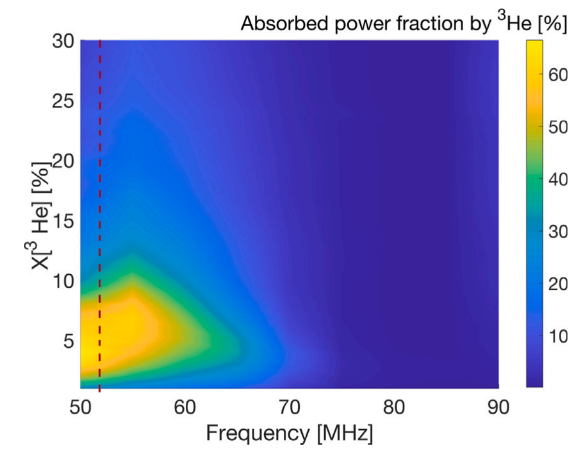

Fig. 2. Single pass absorption of ^{3}He in D plasma as a function of the ^{3}He concentrations and frequency, as Fig. 1.

instance, power variation is typically on the order of 3 dB between 45 MHz and 100 MHz, allowing for the design of amplifiers that do not require a tuning system, while ensuring that the output power deteriorates by no more than 3 dB in the sidebands. A market survey showed that a bandwidth of 30 MHz can be achieved with limited complexity. In general, two different combination philosophies exist. One philosophy is the method adopted in [15], which does not allow for achieving a wide bandwidth, while the other involves a gradual combination in multiple stages, utilizing classical combiners commonly found in microwave engineering, such as Wilkinson combiners, 3 dB hybrids, and $\lambda/4$ transformers. This latter approach allows for achieving the desired bandwidth effectively. On-axis power deposition of ^{3}He and H minorities takes place at 60 and 90 MHz, respectively. These two frequencies were also shown to be preferable for the generation of fast particle [24]. Therefore 60–90 MHz was chosen as final nominal frequency range, looking for the best effort below 60 MHz during the optimization of amplifier design.

3.2. Operational characteristics

Three distinct operational modes for the transmitters are identified and must be adhered to within the DTT ICRH system. These modes, referred to as "operating modes", are defined based on specific working and loading conditions, dictated by DTT operation scenarios or inferred from documented ICRH experiments. They are outlined below:

1. Plasma Experiments:
   - The transmitters operate in pulsed mode, with a maximum pulse length of 50 s and a duty cycle of 1.4%.
   - The RF output (i.e. forward) power must reach a maximum ≥ 1200 kW, with VSWR ≤ 1.5.
   - A monotonic RF output power response is required within the range of 600 kW to 1200 kW to allow for a real-time feedback control of the output power within this dynamic range.
   - The transmitters must function with VSWR values up to 3, with output power as close as possible to the nominal one to ensure safe operation.
   - Pallet failures must not prevent the transmitters from operating until the RF output power is above 1080 kW. This requirement, corresponding to a graceful degradation down to 90% of the maximum RF output power, was deemed as a good trade-off between costs and availability for an experimental machine like DTT.
2. Wall Conditioning [25]:
   - Continuous wave (CW) operation is required for up to one hour every two hours, or through pulsed operation with an equivalent average energy output.
   - The transmitters must deliver a maximum RF output power ≥ 120 kW, maintaining a VSWR ≤ 3, across any phase of the reflection coefficient.
   - The system must handle VSWR levels up to 6 for up to 500 ms at the start of the RF pulse.
3. Antenna Conditioning [3,26,27]:
   - Pulsed operations are conducted with pulse durations ranging from 10 ms to 5 s, and a duty cycle ≤ 1.5%.
   - The transmitters must provide a maximum RF output power ≤ 100 kW with a VSWR ≤ 2, across any phase of the reflection coefficient.
   - A monotonic RF output power response between 2 kW and 100 kW is required, with high precision in RF output power.

Each transmitter must support operation in all modes, one at a time. Switching between operating modes must be possible remotely by operators within a timespan of approximately one minute.

The transmitter efficiency, defined as the ratio of RF power [W] to electrical power [VA], is established to be greater than or equal to 0.52 across the entire frequency range when operating under matched load conditions with an RF output power of 1200 kW. This is a conservative value that does not limit design choices and was considered achievable by all consulted manufacturers. Higher efficiencies can be attained, as required in fusion reactors [28], and will be attained at most frequencies by DTT transmitters themselves.

The gain of each transmitter, defined as a complex function relating its RF output signal to the RF input signal can be varied in magnitude and phase. The variation can be on a pulse-to-pulse basis, with the gain kept constant by a transmitter internal feedback loop during the pulse, or it can be changed in real time through external amplitude and phase references, e.g. according to directions coming from the plasma control system. Gain control is done at the low-level RF section (LLRF), which is part of the transmitter. The input of the latter is indeed a permanently present RF signal with a typical bandwidth of the order of a few kHz. The level of harmonics at the output is less than −20 dBc, while the level of spurious signals at the output is also below −20 dBc.

The settling times for amplitude and phase references are set to 0.5 ms and 1 ms, respectively. The former enables the most widely used analysis techniques based on ICRH modulation [29–31], while the latter reflects the capabilities achievable with current standard technology. When constant magnitude and phase are required for the transmitter gain, the RF output of the transmitter adheres to intra-pulse and pulse-to-pulse stability requirements given in Table 1.

Table 1
Time stability requirements.

Operating mode	Output power	Gain phase	Notes
Plasma experiments	< ±5 %	< ±5°	For RF output powers in [600–1200 kW].
Wall conditioning	< ±10 %	< ±10°	For RF output powers of 120 kW.
Antenna conditioning	< ±5 %	Not required	For RF output powers in [2–100 kW].

3.3. Solid-state technology and modular RF architecture

The production of the first two DTT transmitters was awarded to a consortium of Italian companies, OCEM Power Electronics and SYES, after a comprehensive technical evaluation. Each transmitter will use over 1500 LDMOS transistors, individually monitored in terms of voltage and current, and will employ a multi-stage combiner (Fig. 3) to integrate outputs into a coaxial cable. The adoption of solid-state technology, particularly LDMOS ART2K0 transistors [32], was chosen for their robustness and reliability under high VSWR conditions, supporting both continuous and pulsed operations essential for DTT.

The overall 1.2 MW amplifier is composed of 128 modules, each delivering up to 11 kW CW power with 60 dB gain in the 60–90 MHz range. The layout will be similar to those found in the broadcasting world, and the reference sheet of the pallet can be found in [33]. The 1.2 MW system is housed in four islands, each grouping four amplifier cabinets (Fig. 4), with each cabinet containing two blocks of amplifier modules powered by off-the-shelf, plug-in power supplies, similar to standard power supplies as [34].

The modular design ensures high reliability and scalability, with the ability to maintain reduced power output in the event of a failure. The system is designed for the three operating modes:

- Plasma experiments: Pulsed operation with a 50-second maximum pulse length, achieving a system reliability of over 99.9%.
- Wall conditioning: CW or pulsed operation with reliability exceeding 99.8%.
- Antenna conditioning: Pulsed operation, also with system reliability above 99.9%.

Each amplifier module operates with constant gain and phase, with controllable drain voltage of LDMOS to improve amplifier efficiency. Class C operation is used for most modes, while Class AB is applied during Antenna conditioning for greater power stability.

The main cooling system of the transmitters shall be liquid-based via the water cooling circuit of the DTT site. A connection to the latter will be provided to serve a group of four transmitters, whose cooling shall comply with the following features:

- Liquid: softened water.
- Input pressure = 6 barg.
- Maximum flow rate: 302 m^3/h.
- The input temperature at the start of an RF pulse must be maintained within the range of 15–25 °C.

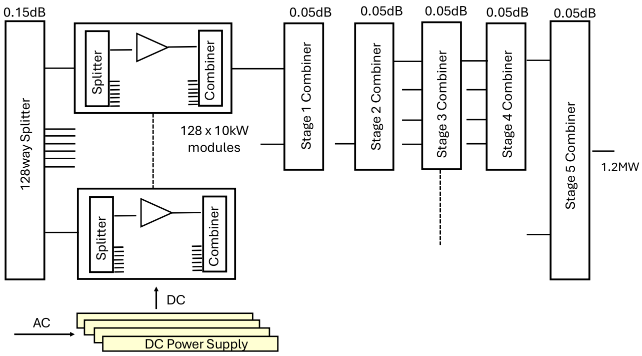

Fig. 3. RF system and power level estimation.

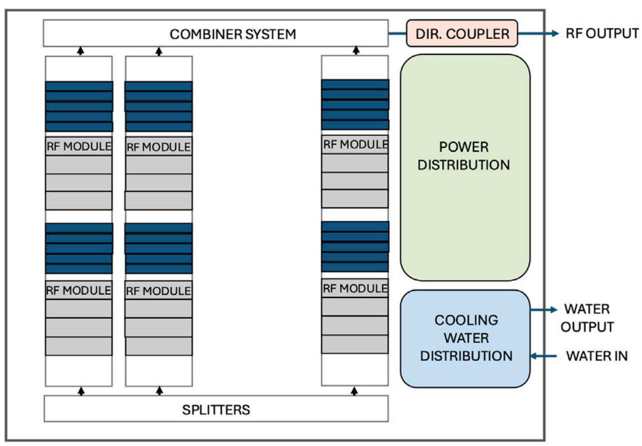

Fig. 4. Structure of the transmitter's cabinet.

4. Grid tube versus solid-state technology in DTT facilities: benefits and limitations

The transition from grid tube technology to solid-state systems in DTT parallels the shift observed in high-voltage modulators, where traditional series tube regulators were replaced by solid-state power supplies. Historically, grid tubes such as tetrodes or diacrodes [35] in transmitters required complex, custom-built high-voltage power supplies (around 20 kV), which also necessitated X-ray shielding and auxiliary systems for filament heating and grid biasing. In contrast, modern solid-state devices like LDMOS operate at significantly lower DC voltages, typically below 65 V, resulting in a 20 dB reduction in phase noise and simplifying power supply requirements.

While solid-state amplifiers require a greater number of low-voltage power supplies, this modular design provides key advantages. These power supplies are standardized, easily replaceable, and can be configured for hot-swappable operation, thereby improving fault tolerance and overall reliability. Furthermore, solid-state technology offers distinct operational benefits, including longer device lifetimes, simplified maintenance, and lower operating costs compared to grid tubes.

Although solid-state amplifiers generally have a lower power density, in the context of DTT's system, their modularity allows for more efficient use of available space within existing infrastructure. For instance, while the solid-state amplifier configuration requires a footprint of approximately 10 x 5 m, the grid tube setup necessitates several rooms to accommodate all components (Fig. 5). As a reference, we based our design on the EAST transmitter [36], but without the installation of a mezzanine.

The flexibility in the deployment of solid-state solutions is a significant advantage for the DTT facility, which operates under specific spatial constraints.

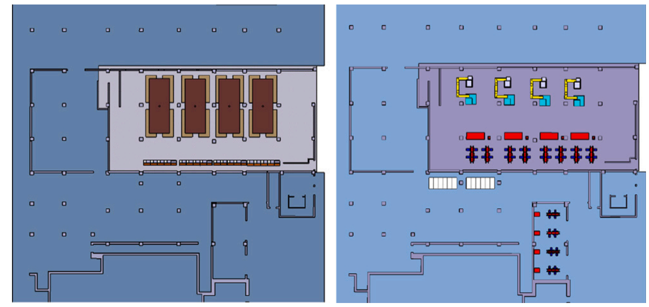

Fig. 5. Solid-state (left) and grid tube (right) amplifier configuration where the column pitch is around 5 m.

From a sustainability perspective, the transition to solid-state technology ensures long-term viability. Grid tubes are becoming increasingly rare and expensive, often resulting in dependency on a single supplier. Solid-state devices, while also subject to potential obsolescence, are mass-produced for a variety of applications, making it more feasible to identify suitable replacements if a specific component is discontinued, even though such replacements may require redesign efforts. Technological advancements in solid-state devices have significantly outpaced grid tube development, which has seen minimal research and innovation in recent decades.

For DTT's ICRH system, solid-state transmitters provide superior flexibility and scalability. Unlike grid tube systems, whose design and performance is not customizable, solid-state RF modules can be combined and tailored to meet specific power output requirements. Additionally, the development and testing of solid-state transmitters are more time-efficient, reducing lead times compared to grid tube-based transmitters that require custom cavity design and extensive validation. In conclusion, although solid-state transmitters may initially involve higher capital costs and represent a novel solution for DTT, their long-term advantages-including enhanced reliability, reduced maintenance, and lower operational costs—clearly justify the investment.

5. Conclusions

This paper has presented a comprehensive overview of the amplification system to be designed for the ICRH system of the Divertor Tokamak Test facility, detailing its design specifications across various operational modes, including plasma experiments, wall cleaning, and conditioning. The adoption of solid-state technology for the entire amplification system marks a pivotal advancement in fusion energy research, addressing both performance and reliability requirements.

The solid-state amplification system represents a significant step forward in the evolution of tokamak-based fusion technologies. Its successful implementation in the DTT facility sets a new benchmark for the development of energy-efficient, reliable, and scalable solutions for plasma heating, further advancing the progress of fusion energy research.

CRediT authorship contribution statement

C. Salvia: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **P. Bettini:** Supervision. **A. Cardinali:** Writing – review & editing, Validation, Supervision. **S. Ceccuzzi:** Writing – review & editing, Supervision, Project administration, Conceptualization. **S. Greco:** Writing – review & editing. **D. Van Eester:** Writing – review & editing, Validation, Supervision, Software, Methodology. **F. Zanon:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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