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IFMIF-DONES RF System

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A R T I C L E I N F O

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A B S T R A C T

The IFMIF-DONES accelerator cavities require around 5.7 MW of continuous RF power at 175 MHz to deliver a 125 mA and 40 MeV deuteron beam at the lithium target. The IFMIF-DONES RF System is composed of 56 RF Stations able to provide up to 200 kW RF power at 175 MHz in CW, delivering a grand total of 7.4 MW.

Such a massive system requires an ambitious approach to be able to comply with the accelerator requirements with a high efficiency and a high availability. The newest advancements in the field of RF systems for accelerators, which are already implemented independently in some facilities, are integrated for the first time in a single system from the early design phases. The result of this approach is the RF Station, which is a totally independent and compact RF module containing all the components needed to feed, control, and protect the accelerator cavities. The amplification technology chosen is the Laterally-Diffused Metal-Oxide Semiconductor (LDMOS) transistor, providing a good efficiency and high robustness. The proposed RF power combination of up to 160 transistors is based on resonant cavity combiner, allowing a single-step combination that highly reduces the losses with respect to more traditional corporate combining schemes. In this proposal, the RF generation relies on a fully digital Low-Level RF (LLRF) providing accurate amplitude/phase control and high flexibility to implement all the required functions for a proper cavity operation. The RF Station has been designed maximizing the modularity and the reliability. In order to achieve the required modularity, the LDMOS transistors have been grouped in Amplifier Modules (AMDs) containing four of them but keeping independent outputs. Furthermore, the AC/DC power converters have also been grouped in modules feeding a common DC bus. The RF Station will have redundant modules to be able to operate properly in any condition, even with some of them failed.

This innovative proposal for the IFMIF-DONES RF System design and detailed information on the RF Stations architecture are presented in this paper.

1. Introduction

The IFMIF (International Fusion Materials Irradiation Facility) project aims to create an irradiation facility generating a neutron flux with a broad energy distribution covering the typical neutron spectrum of a (D–T) fusion reactor. This will be achieved using Li(*d,xn*) nuclear reactions taking place in a liquid Li target when bombarded by a deuteron beam. The associated DONES (DEMO Oriented Neutron Source) project activities are based on the results obtained in the previous IFMIF/EVEDA (Engineering Validation and Engineering Design Activities) phase, presently conducted in the framework of the EU-Japan Bilateral Agreement on the Broader Approach to Fusion [1]. The DONES engineering activities of the EUROFusion Consortium will consolidate the design and the underlying technology to be applied for the IFMIF-DONES facility construction in the early 20′s.

IFMIF-DONES will be the relevant neutron source that can provide the irradiation conditions foreseen for the first wall of the DEMO fusion power plant demonstrator. The 40 MeV deuterons and the 125 mA beam current of the accelerator will be tuned to maximize the neutron flux in a volume of around 500 cm^3 that can house around 1000 small specimens for irradiation [2].

The IFMIF-DONES accelerator is based on a first acceleration stage based on a Radiofrequency Quadrupole (RFQ) up to 5 MeV and a second stage based on a five-cryomodules Superconducting Radiofrequency

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(SRF) Linac (Linear Accelerator) up to the final 40 MeV energy. To match both stages, the Medium Energy Beam Transport (MEBT) system will be used to adapt the beam in transverse mode with quadrupoles and in longitudinal mode with two re-buncher cavities. Therefore, the IFMIF-DONES RF System will be the responsible of feeding all those RF structures: the RFQ cavity, the re-buncher cavities, and the Half Wave Resonators (HWR) used in the SRF Linac. In those structures, the RF energy will be transferred to the accelerated beam particles except for the amount corresponding to the losses in the metallic cavity walls.

Originally, the RF System proposed for IFMIF was based on the RF Modules provided by CIEMAT for the IFMIF/EVEDA phase, which were finally commissioned for the Linear IFMIF Prototype Accelerator (LIPAc). These RF modules rely mainly on tetrode-based amplification stages [3,4], although the first pre-driving stage is based on a commercial solid-state amplifier (just 500 W compared with 230 kW final output). These tetrodes are biased in their optimum working points (better than 60 % efficiency), but the auxiliaries required for their operation (HV anode power supplies, grids and filament power supplies, tetrodes protection system, blower, etc.) reduce the overall LIPAc RF Module efficiency to around 47 %.

Although this RF module design basis used a mature and proven technology, including improvements to enhance the reliability and availability [5], and in spite of the good performance achieved so far, there were still some disadvantages inherent to vacuum tubes: need of high voltage, need of high-power circulator, phase noise, low modularity, complex maintenance, long warm-up time, limited lifetime, and possible obsolescence.

As an early technology demonstrator, the LIPAc MEBT RF Module (see Fig. 1), which is required to feed two re-buncher cavities, was designed to be fully based on solid-state power amplifier (SSPA) technology [4]. The resulting 2×20 kW modular amplifier has been used for the MEBT re-buncher cavity testing [6], has been commissioned in LIPAc [7], and is working with beam flawlessly [8]. The ten SSPA modules of each amplifier are capable of hot-swapping and include a circulator at their output. The complex commissioning process of the tetrode-based LIPAc RF Modules was skipped with the MEBT RF Module (almost a plug and play system). This demonstrator has shown the lack of the tetrode disadvantages and all the benefits of using solid-state transistors for RF amplification, reaching an overall 55 % efficiency.

All the experience extracted from the LIPAc RF System, including the solid-state RF module developed for the MEBT re-buncher cavities, advised the DONES project to change the design baseline to full solid-state amplifiers. Additionally, this change is endorsed by the current trend to adopt solid-state technology for the RF power system in many accelerator facilities around the world [9].

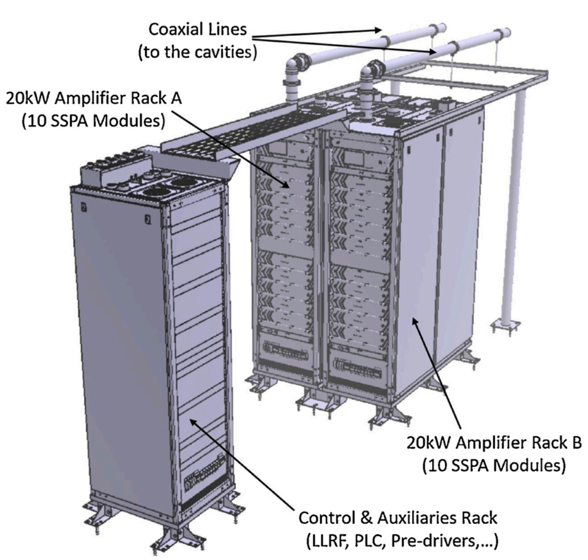

Fig. 1. LIPAc Solid-State RF Module.

Therefore, an innovative proposal for the IFMIF-DONES RF System, based on the latest LDMOS solid-state power amplifier technology and an advanced single-stage resonant cavity combiner, is presented in this paper.

2. Main characteristics

The IFMIF-DONES RF System will generate, amplify, deliver, and manage the required high-power RF signal to the accelerator cavities. The characteristics and quality of this RF signal are key parameters for the proper operation of the IFMIF-DONES particle accelerator, as the electric field accelerating the deuterons is direct consequence of this delivered high power RF. Depending on the accelerator subsystem, specific requirements are necessary, but the common parameters for the RF System are summarized in Table 1.

The RF System will convert the 380 V alternate current (AC) three-phase electrical feeding (around 12 MVA) into the required RF power using solid-state technology. This conversion is done in two steps, as the solid-state transistors require a direct current (DC) bias to amplify an RF signal, so AC/DC converters are the first step in this conversion. Although all this energy conversions have a high efficiency (better than 60 %), there is still 3.8 MW of heat generated in the amplifiers that will be removed and managed using around 441 m^3/h of cooling water provided by the Accelerator Systems Ancillaries.

The RF System is also in charge of reacting to the cavity field variations due to multiple effects (beam loading, thermal dilation, amplifier gain drift, etc.), compensating these phenomena and keeping the amplitude and phase of the accelerating voltage as required, to have a proper acceleration of the deuterons (see Table 1).

The nominal operation mode of the IFMIF-DONES particle accelerator is in continuous wave (CW), so the RF System nominal operation is also in CW. However, the commissioning phases of the accelerator require an exhaustive use of pulsed modes, so the system will be able to provide a wide range of pulses (minimum pulse width of 10 μs and a repetition rate ranging from 1 Hz to 10 kHz).

The RF System will provide the required RF signal to each cavity using standalone RF modules called RF Stations, constituting a first level of system modularity. Each RF Station will feed one cavity except in the case of the RFQ, which will be fed by eight synchronized RF Stations acting as a single RF source, due to the high power required. The RF Stations will be grouped in blocks corresponding to their related cavity subsystems: the eight RFQ cavity inputs, the two MEBT re-buncher cavities, the two low-β SRF Linac cryomodules (containing 8 and 11 HWRs respectively), and the three high-β SRF Linac cryomodules (containing 9 HWRs each). Table 2 shows the power consumption, the heat load generated, and the water flow required for each RF Block.

The design of the RF Station as a completely independent and compact module, self-containing all the components required to feed, control, and protect an accelerator cavity, makes the RF System hardware set to be composed just by 56 RF Station units, which are managed by the RF Local Instrumentation and Control System (LICS). This RF LICS is virtual component based on hardware distributed along the RF

Table 1
RF System main parameters.

Parameter	Value
Nominal Frequency	175 MHz
Total RF Output Power	7.4 MW
Cavity Voltage Stability	±1 %
Cavity Phase Stability	±1°
Harmonics	−30 dBc
Spurious	−50 dBc
Availability	88 %
Emergency Stop Time	10 μs

Table 2
RF Blocks consumption, heat load, and water flow.

RF Block	Power	Heat	Water flow
RFQ	2.7 MVA	849 kW	99 m^3/h
MEBT	54 kVA	17 kW	2 m^3/h
Cryo #1	900 kVA	283 kW	33 m^3/h
Cryo #2	1.6 MVA	489 kW	57 m^3/h
Cryo #3	2.0 MVA	643 kW	75 m^3/h
Cryo #4	2.4 MVA	735 kW	86 m^3/h
Cryo #5	2.4 MVA	763 kW	89 m^3/h
Total	12 MVA	3.8 MW	441 m^3/h

Stations and software running on the RF Stations electronics or the Central Instrumentation and Control System (CICS) computers.

The RF System operation is supervised by means of three different subsystems of the IFMIF-DONES CICS:

- Control, Data Access and Communication (CODAC): the RF System operation is managed interfacing with the CODAC system. Specifically, the RF LICS is connected to the Supervision and Central Control (SCC) subsystem for high-level control and the RF injection is synchronized with the rest of the accelerator systems interfacing with the Time and Synchronization (TS) subsystem.
- Machine Protection System (MPS): The RF System should react to any anomaly with the required speed to avoid any damage to the accelerator or the RF System itself. For that, a wide set of diagnostics and a fast reaction control system allows quickly stopping the RF power and informing the MPS of the anomaly.
- Safety Control System (SCS): The RF System will not be able to inject RF power into the cavities if it is not authorized by the SCS, guaranteeing the staff X-rays safety.

The RF System architecture, containing all the mentioned systems and interfaces, is shown in Fig. 2.

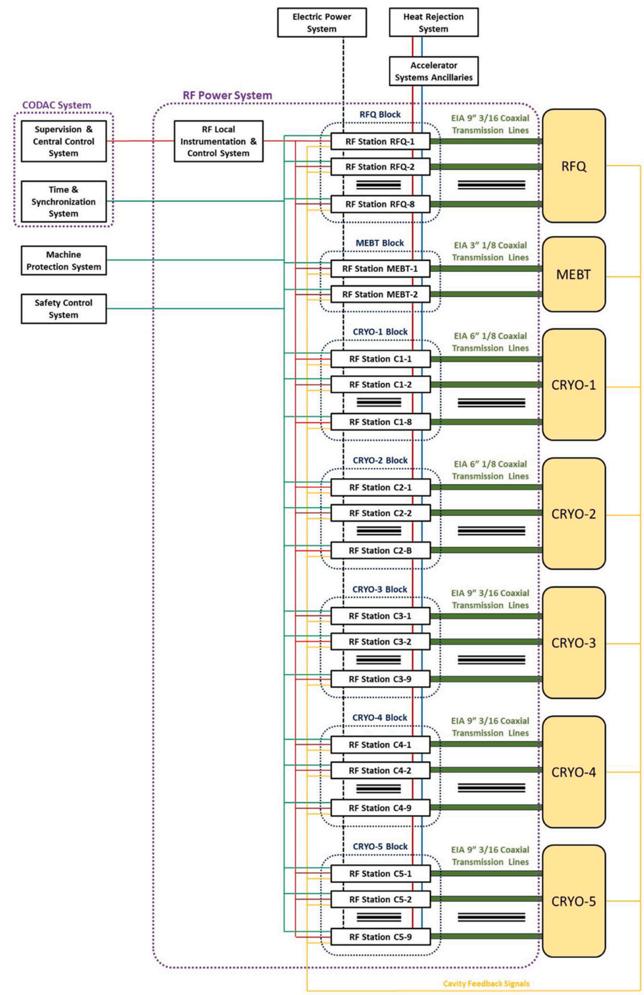

Fig. 2. IFMIF-DONES RF System architecture.

3. The RF Station

The RF Station is based on a full solid-state technology amplifier using LDMOS transistors capable of providing 1.5 kW at 175 MHz with a high efficiency (around 70 %). The transistors will be fed from a DC bus, which will be powered by a distributed high efficiency AC/DC power supply system allowing high modularity and redundancy. The RF output of all the LDMOS transistors will be combined in a single step using an advanced cavity combiner, reducing the losses and increasing the overall amplifier efficiency [10,11]. This alternative has big advantage in operation cost reduction due to the high global efficiency achieved.

One key aspect of each RF Station is the output power, as each cavity requires a different amount of RF power to operate at nominal conditions. The RF power levels required for each RF station (referred to the end of the corresponding coaxial transmission line) are shown graphically in Fig. 3.

The main components of the RF Station are the Low-Level RF (LLRF), the RF Station Control System, the Power Combiner, the Coaxial Transmission Line, the Amplifier Modules, and the AC/DC Power Modules. Additionally, the RF Station has many auxiliaries as the RF signal distribution, the water-cooling distribution, the AC power distribution, and the shared DC bus. All these components inside the RF Station architecture are shown in Fig. 4.

Each RF Station has the basic same configuration, differing in the number of Amplifier Modules (AMD), which depends on the required output RF power, and in the number of AC/DC Power Modules (ADPM), which is related to the number of AMDs to feed with DC power. The AMD and ADPM modules constitute a second level of modularity for the IFMIF-DONES RF System, playing a very important role on the system availability. It is foreseen to have at least three different configurations: up to 40 AMDs (200 kW RF Station) for the RFQ cavity and the high beta HWR cavities of the SRF Linac, up to 20 AMDs (100 kW RF Station) for the low beta HWR cavities of the SRF Linac, and 4 AMDs (20 kW RF Station) for the re-buncher cavities.

The RF Station volume is approximately a 2.2 m diameter and 3 m height cylinder, weighting 8000 kg in a first rough calculation. The 40 AMDs RF Station version is shown in Fig. 5.

3.1. Low-Level RF

The Low-Level RF (LLRF) system generates the primary 175 MHz signal that, after being amplified up to the required level, feeds the accelerating cavity. This low-level RF signal is delivered to the RF Signal Distribution auxiliary subsystem, where it is split to obtain the required number of driving signals (one per each AMD). All the split low-level RF signals provided to the AMDs shall be synchronous and equal in amplitude and phase.

The IFMIF-DONES LLRF will be based on an enhanced version of the LIPAc unit [12] and its main functionalities are:

- *Signal generation*: the 175 MHz signal generation is fully digital (no analog front-ends for frequency up-conversion) and phase locked with the master clock reference of the accelerator.
- *Feedback loop*: comparing diagnostic RF signals coming from the accelerating cavities, the LLRF modifies its output signal (RF drive). The aim is to maintain the required electromagnetic field amplitude and phase in the accelerator cavities, which has critical impact on the beam quality.

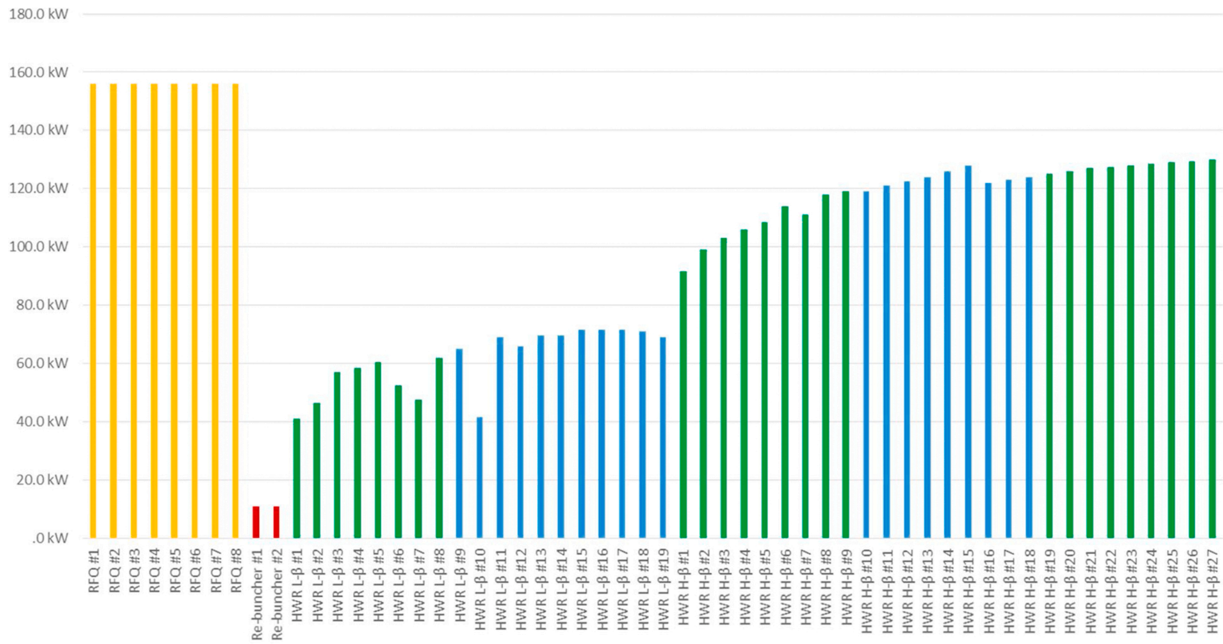

Fig. 3. RF Stations power requirement.

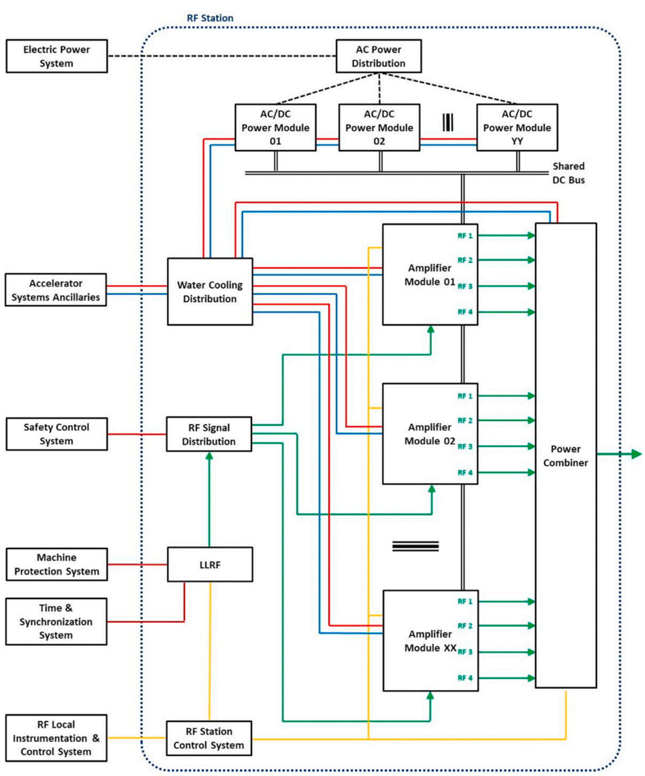

Fig. 4. RF Station architecture.

- *Pulsed operation*: the output signal could be operated in CW, beam pulsed, and conditioning modes. In the beam pulsed mode, the RF drive signal is generated according to the timing signals of the accelerator (provided by the TS subsystem). On the contrary, in the conditioning mode, the pulses configuration is defined automatically by the LLRF integrated conditioning controller or manually by the operator.
- *Diagnostics*: the LLRF does a fully digital acquisition of different kinds of signals (RF, digital and analog) from the accelerator subsystems

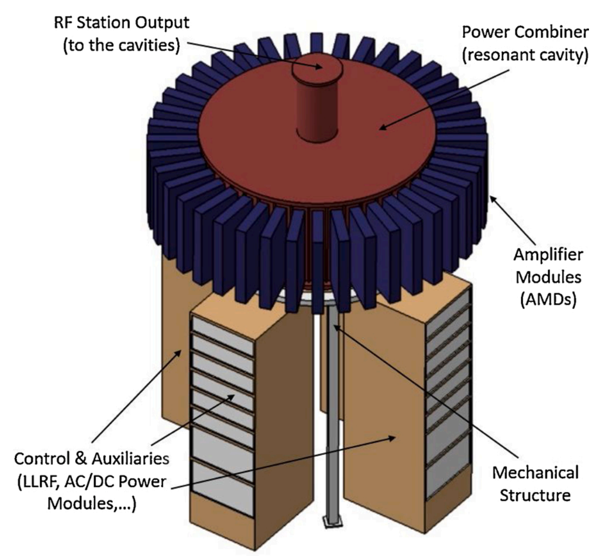

Fig. 5. RF Station (200 kW version with 40 AMDs).

and from the RF Station itself. It is in charge of the monitoring of the signal characteristics, as well as the data storage in memory buffers.
- *RF conditioning*: an integrated controller for the high-power RF conditioning of the accelerator cavities and couplers reacts automatically, adjusting the characteristics of the RF drive signal or abruptly switching off the RF in case of emergency. It is a fully integrated controller, which take into account the vacuum, multipacting, temperature, and arc signals for the conditioning process.
- *Cavity tuning*: an integrated controller manages the resonance frequency of the cavities by acting on the different types of actuators: step-motor for plungers or temperature control systems.
- *Fast interlocks*: several critical signals (arcs, multipacting, vacuum, forward/reflected power levels, internal alarm, MPS trigger, etc.) are monitored and in case of activation or reaching critical values, the RF drive signal is switched off in less than 10μs. All the loops, controllers and diagnostics of the LLRF will be blocked and the system will

remain in that state until the emergency is extinguished and the system is rearmed.

- *Fast Data Logger*: after a fast interlock event or a manual request, the LLRF storages the signals in a memory buffer for analysis (before the event and after it with configurable periods). Additionally, the LLRF stores the fast interlock sequence of the different emergency signals, for troubleshooting.
- *Automatic start-up*: a dedicated controller is in charge of the automatic start or rearm of the LLRF system in a fast and simple way, performing a systematic setup and control sequence, until reaching the nominal operation mode.
- *Frequency shift*: when the resonant frequency of the accelerating cavities drifts from the nominal, the frequency of the RF drive signal changes in order to match it, maximizing the energy transfer and reducing the reflected power.
- *Beam loading compensation*: a feed-forward loop is used to adjust the cavity field amplitude and phase before the beam arrives (filling time), based on the data acquired during the previous beam pulse. In this way, the field generated by the RF and the beam induced field add-up, resulting in the exact required field for acceleration just when the beam enters the cavity. Additionally, a frequency shift can be used during the filling time to match the on-purpose detuning of the cavity compensating the frequency shift generated by the beam. This is a critical function in the IFMIF-DONES accelerator due to the very high current of the beam, which can induce very high field levels, distorting the RF generated field. The LIPAc LLRF has shown a good beam-loading compensation [13], so the DONES unit performance is expected to improve taking into account the beam operation experience.
- *RFQ synchronization*: the RFQ RF Stations behave as a single one, so the eight high power RF feeds are synchronized in time, and balanced in amplitude and phase. The LLRF will be responsible of maintaining such synchronization and balance conditions, including the emergency stops, in which all the feeds are shut down in the same way and at the same time. This synchronous operation has already been tested in LIPAc with good results after the commissioning adjustments [13].

3.2. Amplifier Module

The Amplifier Module (AMD) is the basic component for the main function of the RF Station, which is to generate high power RF. The AMD contains four main amplifying stages (AST) that are based on the latest generation of LDMOS transistors from NXP (MRFX series, model 1K80 H) and a custom input/output matching circuit using planar distributed structures as much as possible, instead of discrete electronic components (see Fig. 6). These four AST are not combined internally in the AMD, as usual in other systems, to take advantage of the single step high efficiency power combiner of the RF Station.

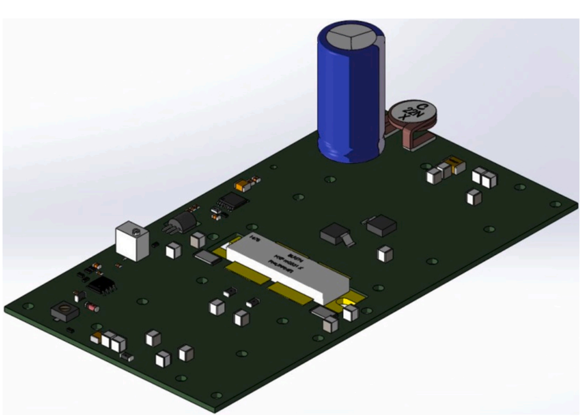

Fig. 6. 3D CAD of the Amplifying Stage.

The design of the AST has been completed and the first prototype laboratory tests have been performed biasing the transistor at 60 V and 65 V. The results demonstrate that it is possible to achieve a 70 % efficiency in the output power range from 1.2 to 1.5 kW at 175 MHz (see Fig. 7), keeping the gain compression at acceptable levels. The high power capability provided by the AST, reduces the number of units required to reach the RF Station output power target, thus reducing the manufacturing cost of the RF System.

Each one of the four main ASTs shall be fed with the same signal, so a four-way splitter divides the signal providing four drives with equal amplitude and phase (see Fig. 8). The signal coming from the RF Signal Distribution of the RF Station (that at the same time comes from the LLRF) has very low power so it is insufficient to drive the LDMOS transistors. This signal must be amplified in the Pre-amplifying Block before splitting in order to reach the AST with an adequate level for final amplification. The Pre-amplifying block is a weak point in the whole AMD reliability so it has been designed to work into the comfort zone of the transistors (linear zone with wide margin) combined with extra robust electronic circuits.

Each AST will be protected against reflected power coming from the power combiner by a full power isolator block, formed by a circulator and its load. This is a key characteristic of the AMD, as the use of solid-state technology allows to distribute the traditional high-power circulator at the output of the complete amplifier in smaller circulators, which protect each AST individually. These smaller circulators are completely passive and avoid the complexity related to the control of the magnetic field coils present in the high-power circulators [13]. The circulators, the loads, the ASTs, and the Pre-amplifying Block will be mounted on a heatsink plate using the coolant flow provided by the Water-Cooling Distribution of the RF Station (see Fig. 9). The heatsink plate has been optimized to increase the power handling and to reduce the operating temperature of the transistors, thus increasing the reliability of the ASTs.

As it has been explained, the AMD has been designed with a high reliability in mind in order to avoid any failure during the IFMIF-DONES irradiation periods and to be repaired, if required, during the yearly-programmed maintenance periods. Additionally, it has been designed to be assembled in a simple and easy way, so in case of failure, the AMD unit can be replaced by a spare very quickly, reducing the impact on the overall availability of the IFMIF-DONES facility.

3.3. Power Combiner

The power combiner of the RF Stations is a high efficiency modular cavity combiner. It is the output of the RF Station and it acts like the mechanical core, as it will support all the Amplifier Modules.

A modular design has been selected, in order to have flexibility in the number of inputs. The cavity wall is created using plates, which can incorporate current loops as magnetic coupled power inputs or they can be blind. The output is an electric coupling antenna, where all the power

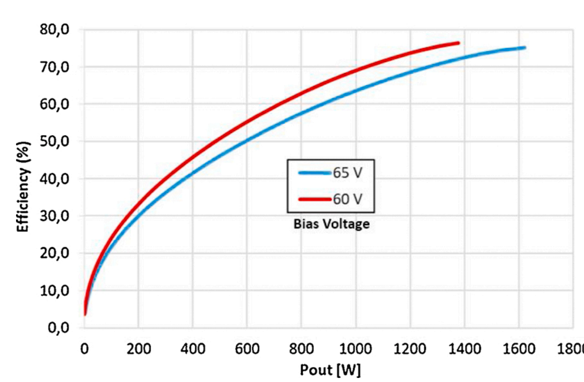

Fig. 7. AST prototype efficiency at different output power levels.

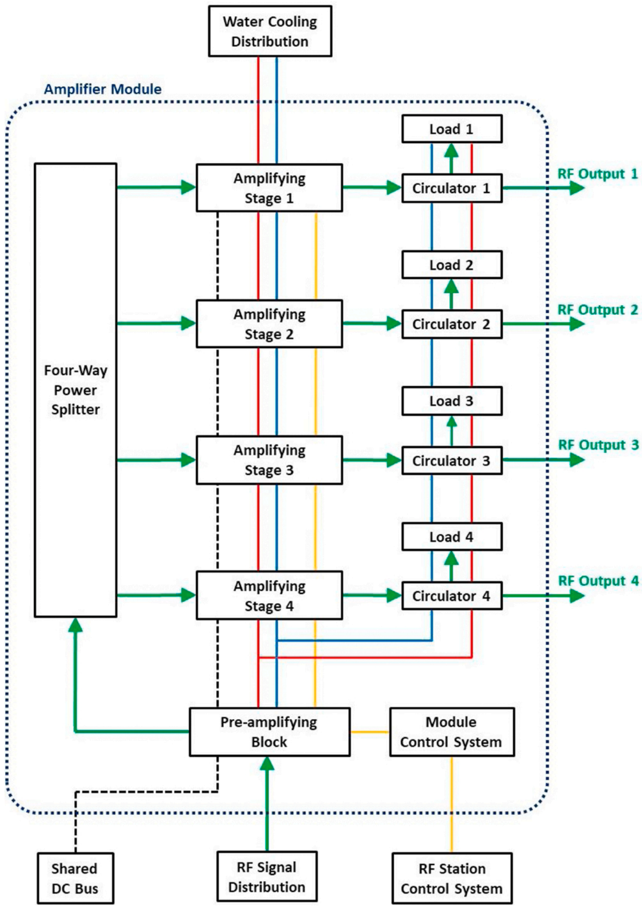

Fig. 8. Amplifier Module architecture.

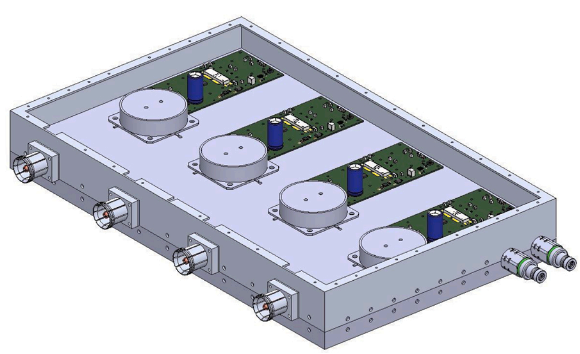

Fig. 9. 3D CAD of the Amplifier Module.

of the inputs is extracted from the resonant cavity. This modular design has been validated experimentally, testing it up to 100 kW in pulsed mode (duty cycle up to 4%) and up to 24 kW in CW, using the first manufactured prototype [10,11].

The industrial version of the RF Station Power Combiner will be able to withstand at least up to 200 kW (the power generated by the 40 AMD version of the RF Station) and will be configurable up to 160 inputs, distributed as four inputs per plate. The inputs will have 7/8″ type connectors for fast and easy connection (see Fig. 10). The combination losses are expected to be better than 0.25 dB (around 95 % efficiency) using copper plating on the inner surfaces of the aluminum cavity. This efficiency means that the maximum heat dissipation on the combiner will be less than 8 kW in the worst case (RFQ RF Stations). Compared with standard multi-staged combination, this is the biggest advantage of the cavity combiner approach (even taking into account the need of isolation on the AMDs, meaning additional 0.21 dB losses due to the circulators).

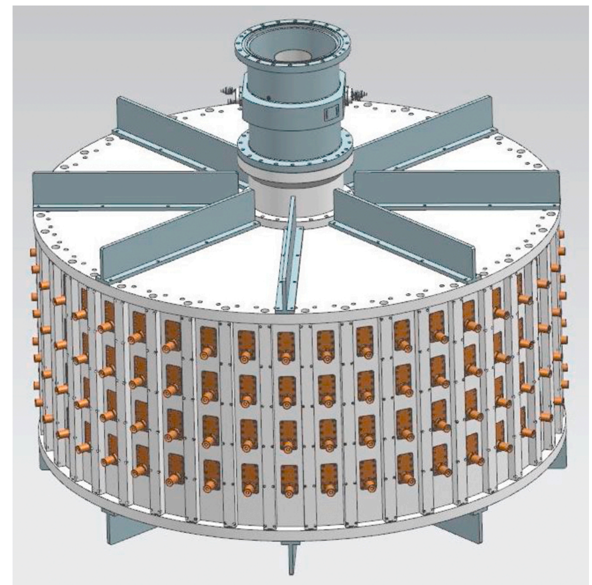

Fig. 10. 3D CAD of the RF Station Power Combiner.

This industrial version has a set of cooling channels to keep the temperature of the cavity walls as constant as possible to avoid geometry deformations. Its cooling architecture is flexible (cooling channels in series/parallel configuration) in order to be able to adjust to the different power dissipations expected for each RF Station configuration. The Power Combiner has a mechanical device (controlled by the RF Station LLRF) to modify the geometry of the cavity. In this way, the RF Station is able to keep constant the resonant frequency of its cavity combiner, thus optimizing the combination efficiency and minimizing the reflected power back to the AMDs.

3.4. *Coaxial lines and radiation shielding*

Three kind of coaxial lines will be used for the IFMIF-DONES RF Stations:

- Thirty-five EIA 9 3/16″ lines (for the RFQ and the High-β Cryomodules)
- Nineteen EIA 6 1/8″ lines (for the Low-β Cryomodules)
- Two EIA 3 1/8″ lines (for the MEBT)

The RF Stations will be installed in the floor directly above the accelerator vault. The routing for the coaxial lines will go through the RF area floor, down on the room next to the accelerator vault and through the lateral wall to reach the accelerator cavity couplers. There will be U-shapes on the RF Station and cavity coupler sides for easy disassembly to allow a fast replacement of damaged components (see Fig. 11).

The coaxial line penetrations through the accelerator room wall are weak points on the concrete radiation shielding of the vault. To keep the radiation classification of the vault adjacent room, the coaxial lines routing allows to build an extra neutron shielding using an additional concrete wall (colored in green in Fig. 9) and a removable shield of polyethylene (red dotted in Fig. 9).

Due to thermal expansion or shrinking, the cavity couplers displace during accelerator operation or start-up. This means that it is required to have a complex system to avoid stress on the ceramic window of each cavity coupler. Each coaxial line will have a flexible section at the coupler side to be deformed as the coupler moves, reducing the stress applied at the interface, compared to a fixed flange end.

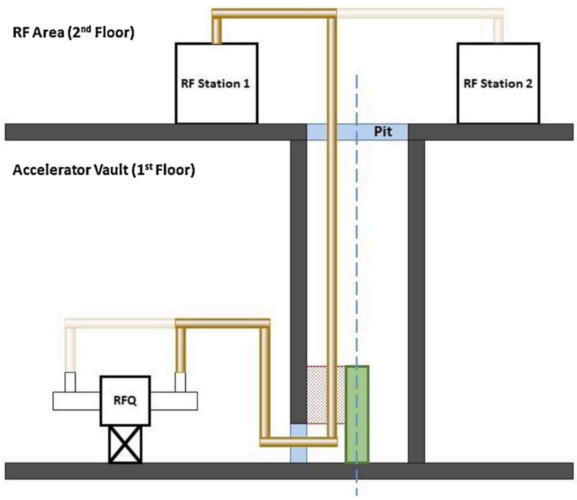

Fig. 11. Coaxial lines routing schematic.

Each coaxial line will be designed to use the minimum possible number of elbows and optimizing the length, thus minimizing the losses. The insertion losses will be less than 0.05 dB, meaning that the maximum dissipated power in the coaxial lines will be around 2 kW. This heat load will be released by natural convection to the related rooms and managed by the HVAC system of the IFMIF-DONES facility.

4. Conclusions

The IFMIF-DONES RF System has been designed taking into account the newest advancements in the accelerator RF systems field. For the first time, an RF system has included all these enhancements from the preliminary design phases, resulting in a compact and independent module (the RF Station) containing all the required components to feed, control, and protect one accelerator cavity. For this reason, the RF System is a modular system composed just by 56 RF Station modules, which are easily installed and do not need additional components.

The RF Station has been designed aiming to reach the highest efficiency ever in a system as massive as the RF System for the IFMIF-DONES facility, which will host one of the most powerful and highest current accelerators in the world. The power capability and efficiency at transistor level have been tested showing that the AST is able to provide up to 1.5 kW with an efficiency better than 70 %. The single stage power combiner is one of the most advanced in the world and has been tested showing that all the AST outputs will be combined with a minimum efficiency of 95 %. All these results, combined with the expected high efficiency of the AC/DC converters, result in an overall AC to RF efficiency better than 60 % for the complete RF System, which is cutting-edge SSPA technology applied to particle accelerators.

The IFMIF-DONES RF System general architecture has been defined and an advanced solid-state modular RF Station is under development. Although more conventional SSPAs could be used for the system, an innovative and promising architecture is proposed in this paper, which will allow reaching unprecedented levels in terms of efficiency, availability, maintainability, and cost.

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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