Fusion Engineering and Design 189 (2023) 113475

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

High power experiments of the Prototype Solid State RF System for IFMIF-DONES

Cristina de la Morena [a,*], David Regidor [a,b], Daniel Iriarte [c], Eduardo Ugarte [c], Saša Dragaš [d], A.J. Martínez [d], Joaquin Molla [a], Angel Ibarra [a]

[a] *Laboratorio Nacional de Fusión (LNF), Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[b] *Universidad Nacional de Educación a Distancia (UNED), Madrid, Spain*
[c] *Broad Telecom SA (BTESA), Leganés, Spain*
[d] *RYMSA Sener Aeroespacial, Arganda del Rey, Spain*

ARTICLE INFO

Keywords:
IFMIF-DONES
Accelerator-based neutron source for fusion materials testing
Radiofrequency power systems
Solid-state amplifiers
Resonant cavity combiner

ABSTRACT

The current trend in the radiofrequency (RF) power systems of many large scientific facilities is the use of solid-state power amplifiers (SSPAs). When it is feasible, for mid-range power levels at frequencies below 1 or 2 GHz, replacing vacuum technology for solid-state (SS) entails significant advantages. Consequently, SS technology has been also selected for the RF Power System of IFMIF-DONES (International Fusion Materials Irradiation Facility – DEMO (DEMOnstration power plant) Oriented Neutron Source). IFMIF-DONES is one of the central facilities of the European roadmap towards fusion electricity, necessary for the validation and qualification of the materials capable to withstand the harsh conditions inside future fusion reactors. Nevertheless, reaching the high power levels of vacuum technology with SSPAs entails the combination of many SS devices. Hence the search for efficient RF power combination techniques is critical in the development of SSPAs.

Resonant cavity combination is an innovative technique that provides a high-power and high-efficient combination in a single step. This minimizes the overall combination losses and reduces the size compared with conventional corporate combination schemes. Two prototype cavity combiners at 175 MHz have been designed and manufactured. The first prototype was validated up to 24 kW in continuous wave (CW) and 100 kW in pulsed mode (duty cycle DC=4 %). The conclusions obtained from those experiments revealed the need for temperature control and/or detuning compensation in the cavity combiner to maintain high efficiency at high-power levels in CW. The second prototype is a water-cooled 160-input cavity combiner capable to combine up to 240 kW in CW. It has been validated at 100 kW in CW, using a witty variant in the experimental test bench that simplifies the experiment. This paper presents the design and small-signal characterization of this 160-input cavity combiner, as well as the results of the high-power validation experiments.

1. Introduction

SS technology advantages compared with vacuum-tube technology are unmistakable: easier operation and maintenance, better availability and reliability, high modularity with subsequent redundancy and flexibility, more safety due to the absence of high voltage, better phase noise performance, longer lifetime, hot-swapping during operation, and faster start-up. The first SSPAs for scientific facilities appeared at LURE-Orsay in the 1990s [1], followed by SOLEIL synchrotron in the 2000s [2]. The maturity of the SS technology and its progressive cost reduction have led many large scientific facilities to upgrade or develop their RF power systems in SS [3,4]. The fusion community could currently apply this technology for the Ion Cyclotron Resonant Heating (ICRH) Systems, as they use low-frequency ranges around tens of MHz.

Following this tendency, the IFMIF-DONES RF Power System will be fully based on SS technology [5]. The IFMIF-DONES facility will be a relevant fusion-like neutron source for the study and validation of the materials that will form future fusion reactors [6,7]. The neutron flux will be generated by the interaction between a liquid lithium target and a deuteron beam produced by an RF linear accelerator at 40 MeV and

---

Abbreviations: DONES, Demo Oriented NEutron Source; IFMIF, International Fusion Materials Irradiation Facility.

* Corresponding author.

E-mail address: cristina.delamorena@ciemat.es (C. de la Morena).

https://doi.org/10.1016/j.fusengdes.2023.113475
Received 28 October 2022; Received in revised form 27 December 2022; Accepted 9 January 2023
Available online 26 January 2023
0920-3796/© 2023 Published by Elsevier B.V.

125 mA CW current. The Linear IFMIF Prototype Accelerator (LIPAc), a reduced version of the IFMIF-DONES accelerator, is currently in the commissioning phase in Japan [8]. The experience from the SSPAs developed for the LIPAc RF Power System has also favored the decision of using SS in IFMIF-DONES [9,10].

Achieving the same power levels as vacuum tubes requires combining the RF power of many transistors outputs. The RF combination strategy in SSPAs is traditionally based on the use of a tree or corporate combining configuration, where several combination stages are placed in cascade. As the target power increases, more combination stages are required, with the subsequent increment in the overall combination losses. Consequently, looking for an efficient combination technique is key in SSPAs.

Resonant cavity combination is a high-power single-step combination technique with significantly lower losses and smaller size concerning corporate-combining topology. Although this combination technology is not currently widespread, several projects have bet on this solution. The most advanced one is the Super Proton Synchrotron SSPAs of CERN (European Organization for Nuclear Research) [13], whose cavity combiner design is based on that developed by ESRF (European Synchrotron Radiation Facility) [14]. The ESRF approach has been also followed in SPRING-8 [15], Advanced Photon Source (APS) at Argonne National Laboratory [16], PIP-II at Fermilab [17], and IFMIF-DONES [11,12]. From the preliminary low-medium power tests, some authors pointed out the need for water cooling to maintain high efficiency for high power levels in CW. This issue has been taken into account in the design of a second cavity combiner prototype for IFMIF-DONES. It is a water-cooled 160-input cavity combiner capable of combining up to 240 kW at 175 MHz, which will be presented in this paper together with its experimental characterization.

The strategy followed by most authors for the high-power validation of the cavity combiner is based on its integration with SSPA modules, which complicates the independent characterization of the cavity combiner. Furthermore, increasing the power of the validation experiments requires more amplifier modules, which raises the complexity (amplitude and phase balance among amplifiers is required) and cost of the experiment. A different characterization method was applied in the first IFMIF-DONES prototype tests [11,12], using a high-power source for feeding the cavity combiner output (back-feeding test) and validating it in splitter mode, as it has a symmetrical response. The same approach has been recently followed by APS [16]. This method requires placing high power loads or additional combiners at the cavity ports, in order to dissipate the power. Then the experiment can be likewise expensive if the number of cavity ports is large. An alternative strategy has been followed in this paper, which simplifies the assembly and reduces the high-power components required in the test bench.

2. The IFMIF-DONES RF power system

The IFMIF-DONES RF Power System (RFPS) will be composed of 56 RF Stations operating at 175 MHz in CW: 8 RF Stations of 200 kW for the radiofrequency quadrupole (RFQ); 2 of 20 kW for the re-buncher cavities of the Medium Energy Beam Transport line (MEBT); and 46 for the Superconducting RF linac (SRF linac), with powers between 40 and 130 kW. The RF Station is the stand-alone element of the RFPS that feeds and controls one accelerating cavity. It constitutes one complete and independent RF line [5].

The block diagram of the RF station proposed for IFMIF-DONES is presented Fig. 1. The SS Amplifier Modules (AMD) are connected to a multiple-input cavity combiner in a radial distribution. Each AMD is composed of four Amplifying Stages based on cutting-edge LDMOS (Laterally-Diffused Metal-Oxide Semiconductor) transistors providing a max. of 1,5 kW. The four AMD outputs are directly connected to the cavity combiner. The other elements (Low Level RF System, RF signal distribution, Control System, AC/DC modules, and AC power distribution) are located below the combiner and the AMDs. The cavity combiner design is modular: its lateral surface is not exactly cylindrical but it is formed by forty flat plates that can include input ports or be blind. Therefore, the 56 IFMIF-DONES RF stations, which require different output power levels, can be configured using the same architecture, just modifying the number of AMDs and input ports in the cavity combiner. Fig. 1 shows the case of a 200 kW RF Station with 40 AMDs, therefore 160 transistors and 160 inputs in the cavity combiner. For a 100 kW RF Station, only 20 AMDs (80 transistors) would be required, then the cavity combiner would include input ports in only 20 plates and the remaining 20 plates would be blind. This flexibility entails great advantages in terms of standardization for series production, spare components acquisition, and maintainability.

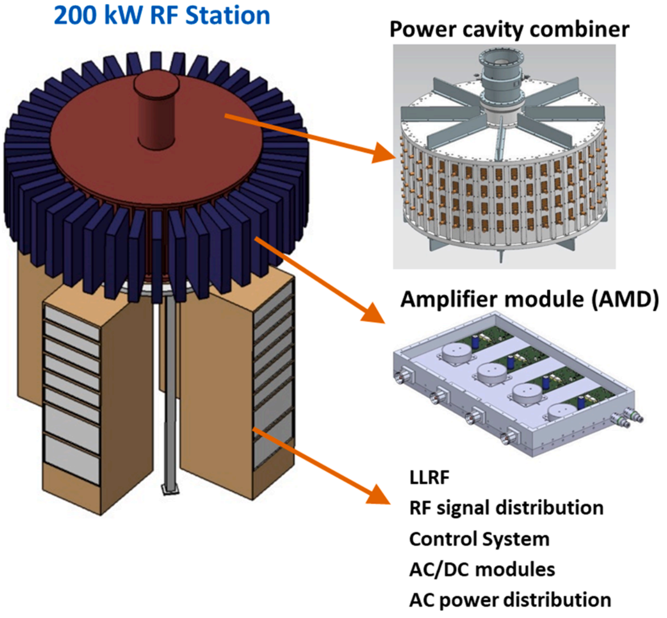


Fig. 1. Architecture of the IFMIF-DONES RF station (200 kW case, with 40 AMDs).

3. Prototype 160-input cavity combiner

The first IFMIF-DONES cavity combiner prototype was validated in an experimental campaign up to 24 kW in CW and at 100 kW in pulsed mode (DC = 4%) at 175 MHz [11,12]. The tests demonstrated very promising results in terms of combination efficiency, in the range of 91 - 95 %, but also revealed the need for water cooling and detuning compensation if high efficiency is wanted to be maintained for high power levels in CW. In addition, enhancement in the shielding was also identified as a future improvement. These issues have been taken into account in the design of a new second prototype, which is a water-cooled 160-input cavity combiner capable of combining up to 240 kW at 175 MHz. Its picture is shown in Fig. 2.

Like the ESRF combiner and the first IFMIF-DONES combiner prototype, the new 160-input cavity combiner is a quasi-cylindrical forty-sided prism. Each of the forty plates incorporates four current loops, resulting in a 160-input port combiner. The number of input ports can be reconfigured as a multiple of four up to 160, by substituting the four-input plates with blind plates. Then a port-reconfigurable cavity combiner is obtained using the same chassis and structure. Nevertheless, a good shielding performance must be ensured to avoid RF leakages through the joints of the walls. The combiner includes a mechanical tuning system, which is currently manually controlled. The upgrade towards an automatic tuning system, directly controlled by the Low Level RF (LLRF) System, may be easily implemented.

For the cavity input ports, 160 terminations have been fabricated with 7/8″ fast-type connectors (not threaded) for simplifying dis-/

Fig. 2. 160-input cavity combiner prototype.

connections (Fig. 3). They have been designed to be easily convertible into 50 Ω loads, for small-signal measurements, or into short circuits, for high-power experiments.

4. Experimental validation

4.1. Small-signal measurements

The scattering parameters (S-parameters) measurements have been carried out using the R&S®ZNB4 Vector Network Analyzer, together with the R&S®ZN-Z84 Switch Matrix for increasing the number of test ports to twenty-four. Fig. 4 shows the measured output return loss ($|S_{out,out}|$ in dB) of the cavity combiner. Note that the resonance frequency is located 20 kHz above 175 MHz, as the temperature of the cooling water was quite cold (13 °C) when the measurements were carried out (January). However, the resonance frequency can be adjusted ± 1 MHz around 175 MHz with the combiner tuning system, maintaining the response. The measured amplitude ($|S_{out,k}|$, being $k = 1,\ldots,160$) and phase ($\Phi S_{out,k}$) transmission parameters are presented in Figs. 5 and 6, respectively. Ideal amplitude transmission is $1/\sqrt{N} = -22.04$ dB, being N the number of inputs of the cavity combiner. For a proper design, it is crucial to achieve a good amplitude and phase balance in all ports. The measured variation range among all ports is 0.37 dB in amplitude and 3 ° in phase.

From the small-signal measurements, the main parameters of the

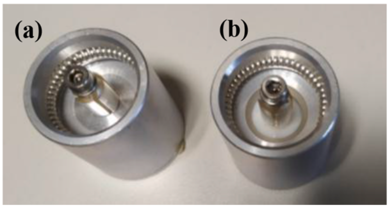


Fig. 3. Fabricated terminations (a) short circuit (b) 50 Ω.

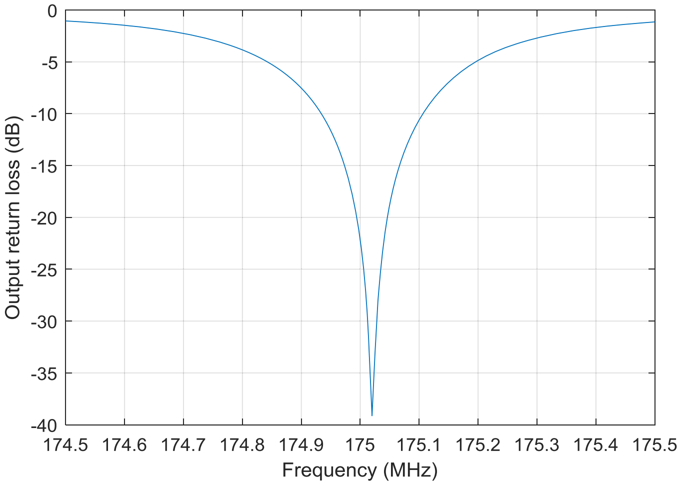


Fig. 4. Measured output return loss (cooling water temperature = 13 °C).

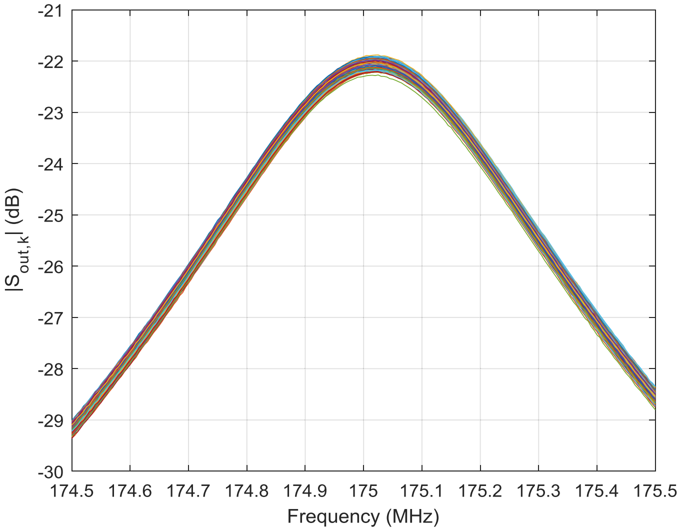


Fig. 5. Measured amplitude transmission parameters, k={1,..,160}.

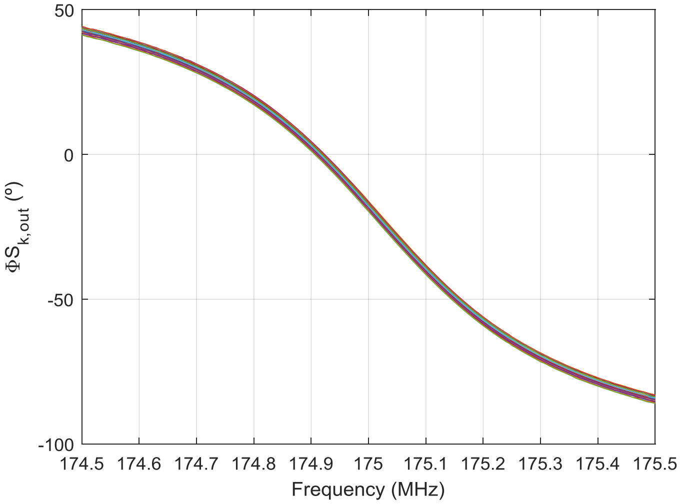


Fig. 6. Measured phase transmission parameters, k={1,..,160}.

Table 1
Measured main parameters of the cavity combiner.

Parameter	Measured value
Resonant freq. f_0 (MHz)	175 ± 1 (adjustable)
Bandwidth BW (kHz)	511.00
Quality factor Q	527.167
Comb. losses at f_0 (dB)	0.01
Comb. efficiency (%)	99.76

160-input cavity combiner can be obtained, which are compiled in Table 1. Combination losses are calculated as follows:

$$Comb.\ losses = \left|\sum_{k=1}^{N} S_{\mathrm{out},k}\right|^2 \Big/ N \tag{1}$$

And combination efficiency is obtained from:

$$Comb.\ efficiency\ (\%) = 10^{\frac{-Comb.\ losses\ (dB)}{10}}100 \tag{2}$$

The results show very low combination losses: 0.01 dB, which results in 99.76 % in terms of combination efficiency. The measured bandwidth is wider than that obtained with the first prototype, as the height of the combiner has been increased in this new prototype.

4.2. High power tests results

The test bench for the high power experiment is shown in Fig. 7. The output of a high-power RF source is introduced into the cavity combiner, whose ports are loaded with short circuits. As the cavity combiner is a symmetrical device, it can operate in both combining and splitting modes. Then, the RF source output signal is divided into 160 signals, which are reflected in the 160 short circuits and combined again by the cavity combiner towards the RF source. The RF source is protected against reflected power by a high-power circulator with a 200 kW load, which will dissipate the power coming from the cavity combiner in the experiment. This experiment configuration is useful for validating the cavity combiner at high RF power, it is indeed a worse situation than in nominal operation mode, where all ports will be loaded with 50 Ω due to the amplifiers, as in this case double power is dissipated in the cavity due to the round trip losses. Therefore, from the thermal point of view, it is equivalent to validating the cavity combiner with double RF power in combination mode. However, the measured combination losses will not be exactly equal to that obtained from S-parameters, which are by definition referenced to 50 Ω, but an estimation.

The RF source that has been used for the experiment is the prototype tetrode-based RF chain manufactured for the RF System of the LIPAc (Linear IFMIF Prototype Accelerator) project [9]. It is a 175 MHz 200 kW RF chain composed of three amplification stages: a first solid-state pre-driver, and two tetrodes as driver (Thales TH561) and final (Thales TH781) amplifiers. The 175 MHz signal is generated by the LLRF System, which is the same system developed for the LIPAc Project [18].

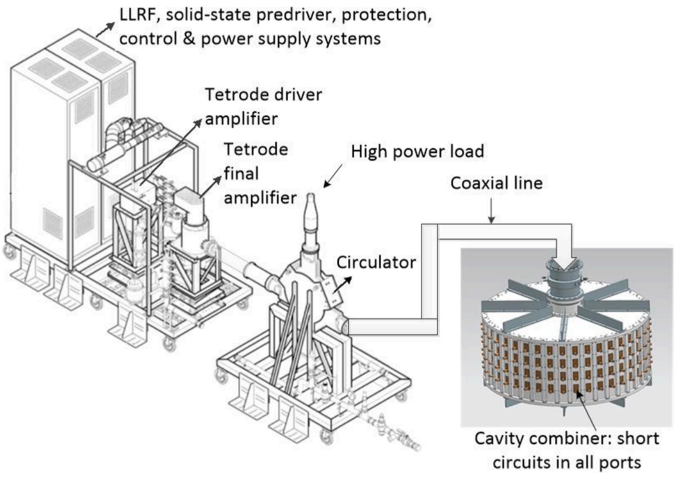


Fig. 7. Test bench for the high-power experiment.

A picture of the high-power experiment is presented in Fig. 8. The 160-inputs cavity combiner was excited with 100 kW in CW for 2 h and 45 min. Meanwhile, the following measurements were taken:

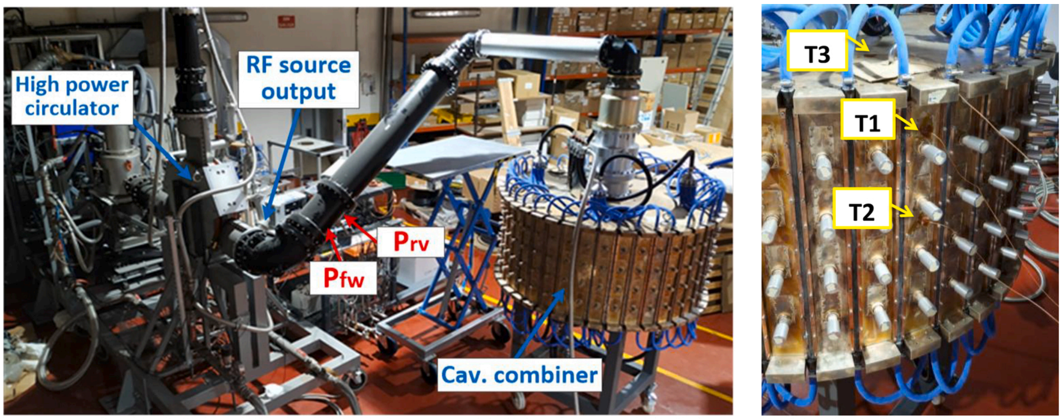
- RF signals measurements: the incident (P_{fw}) and reflected (P_{rv}) powers were tested through a bidirectional coupler at the points indicated in Fig. 8(a), using the KEYSIGHT N1914A power meter and N8482A power sensor.
- Temperature measurements: the temperatures in the external cavity walls were measured with thermocouples placed at the points indicated in Fig. 8(b): T1 (close to an upper port), T2 (between two ports), and T3 (at the upper cover).
- RF leakage measurements: using an electromagnetic field meter, the RF leakage through the cavity walls to the outside was measured.

The time evolution of P_{fw}, P_{rv}, and temperatures T1-T3 are presented in Fig. 9. Combination losses can be estimated as half the difference between the incident and reflected powers measured in the bidirectional coupler, and combination efficiency is obtained from losses following Eq. (2).

The time evolution of combination efficiency is shown in Fig. 10. No action was applied in the cavity tuning system during the test. The conclusions derived from the results are described below:

- Temperature behavior: temperatures in the external cavity walls increase from 20 °C, when power is off, up to 42 °C at 100 kW CW at the end of the test (note that the dissipated power in the cavity is equivalent to that obtained with 200 kW in nominal operation due to round trip losses). At the beginning of the test, the temperature in the cavity upper cover (T3) is lower than in T1 and T2 (points closer to the input ports), but the three temperatures converge at the end of the test. The improvement due to the cooling system is evident: with the first cavity combiner prototype, which had no cooling system, the combiner temperature reached 52 °C after 3 h of nominal operation at 24 kW CW [12].
- Combination losses/efficiency: The difference between P_{fw} and P_{rv}, and consequently the combination losses, gets smaller as the temperature increases, as the resonant frequency approximates the nominal value of 175 MHz. According to the measured S-parameters, the resonant frequency was 175.02 MHz without RF power and 13 °C in water, so when the temperature increases due to the high RF power, the cavity structure dilates and the resonant frequency decreases. At the end of the test, combination losses are 0.155 dB, which means 96.49 % in terms of efficiency. However, the trend of the curve reveals that lower values could be achieved.

  Note that P_{fw}-P_{rv} includes the losses produced in the cavity combiner (both, division losses and combination losses) but also the losses of the different elements in the test bench (see Fig. 8): elbows, coaxial lines, adaptors, etc. In addition, as the RF signals are measured through bidirectional couplers with a low coupling factor (60–65 dB), calibration errors must not be overlooked. Moreover, the N8482A power sensor has a measurement uncertainty of ± 0.35 %. Therefore, a deviation in the measured combination losses is inevitable due to the measurement uncertainty and the additional elements in the test bench. Furthermore, in this experiment the cavity combiner is loaded with short circuits instead of 50 Ω, so the measured combination losses will not be exactly equal to that obtained from S-parameters, which are by definition referenced to 50 Ω.
- Shielding: the electric field was measured near the cavity combiner, proving that very good shielding has been achieved in this new



(a) (b)

Fig. 8. Picture of the high-power experiment and measurement points of (a) RF signals and (b) temperatures.

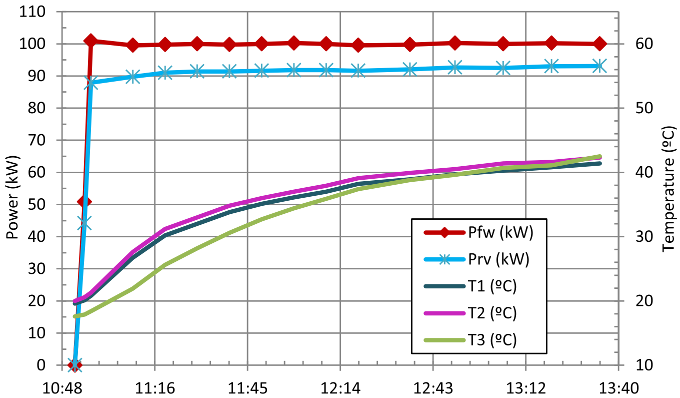


Fig. 9. Test results of the 100 kW CW validation experiment versus time: incident/ reflected powers and temperatures.

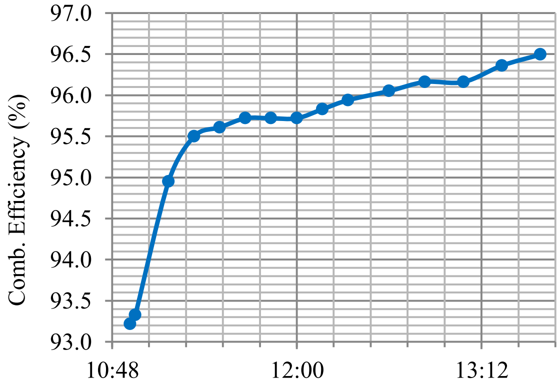


Fig. 10. Test results of the 100 kW CW validation experiment versus time: combination efficiency.

prototype: 8.4 V/m (Max. Avg. value@100 kW). Note that with the first cavity combiner prototype 99 V/m was measured [12].

The combiner tuning system was in a fixed position during the experiment, precisely to study the temperature evolution in order to optimize the configuration of the cavity combiner cooling system, so the resonance frequency of the cavity combiner was not perfectly tuned at 175 MHz. In normal operation conditions, the tuning system will integrate a stepper motor controlled by the LLRF, which will be able to automatically tune the combiner during the warm-up if optimal efficiency is also required during this process. In order to find the optimal matching point, a sweep in the RF source frequency was applied. This is possible due to the flexibility provided by the used fully digital LLRF [18], which can shift its output frequency ± 350 kHz around $f_0 = 175$ MHz. In this case, P_{fw} and P_{rv} were measured using a spectrum analyzer to increase accuracy. The measured combination efficiency as a function of the frequency deviation concerning $f_0 = 175$ MHz is presented in Fig. 11. The results show that matching point at those temperature conditions (T1 = 29.9 ºC, T2 = 30.8 ºC, and T3 = 23.3 ºC) is located 20 kHz below 175 MHz. At that point, very high efficiency is obtained (> 99 %), in accordance with the small-signal measurements.

5. Conclusions and future work

A 175 MHz water-cooled 160-input cavity combiner has been developed and validated up to 100 kW in CW. An alternative strategy for the high-power validation experiments has been presented in this paper, which reduces the number of high-power components required for the experiment and simplifies the test bench. The combination efficiency has been confirmed to be higher than 99 % with both small-signal and high-power tests. Resonant cavity combination has been demonstrated to provide a highly efficient combination of multiple signals in only one step. Consequently, it has been proposed for the development of a future 200 kW SS RF Station prototype for the IFMIF-DONES RF System, instead of using a traditional corporate combination. The next step is to validate the cavity combiner at 200 kW in CW, the highest power required by the IFMIF-DONES accelerator cavities, to definitively demonstrate its viability for the RF Power System of IFMIF-DONES.

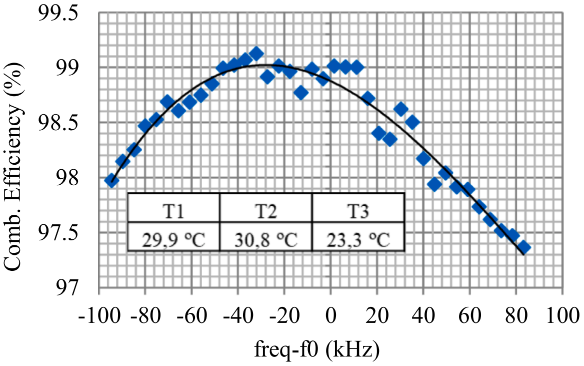


Fig. 11. Measured combination efficiency when modifying the RF source frequency.

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.

Data availability

No data was used for the research described in the article.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

This work has received funding from the Spanish Centre for the Development of Industrial Technology (CDTI) under the 2016 CIEN program (IDI-20160850, ACTECA project) and the 2019 MISIONES program (MIG-20201051, FUSION FUTURE project).

References

[1] J.-M. Godefroy, J. Polian, F. Ribeiro, T. Ruan, MOSFET RF power amplifier for accelerator applications, in: Proc. of 6th European Particle Accel. Conf. (EPAC 98), Stockholm, Sweden, 1998 pp.e-proc. 1811.

[2] P. Marchand, T. Ruan, F. Ribeiro, R. Lopes, High power 352-MHz solid state amplifiers developed at the synchrotron SOLEIL, Phys. Rev. ST Accel. Beams 10 (2007), 112001.

[3] P. Marchand, Review and prospects of RF solid state power amplifiers for particle accelerators, in: Proc. of IPAC17, Copenhagen, Denmark, 2017, pp. 2537–2542.

[4] J. Jacob, High power RF solid state amplifiers for accelerators and storage rings, in: 60th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (FLS2018), Shangai, China, 2018.

[5] D. Regidor, et al., IFMIF-DONES RF system, Fusion Eng. Des. 165 (2021), 112322, https://doi.org/10.1016/j.fusengdes.2021.112322.

[6] A. Ibarra, et al., The European approach to the fusion-like neutron source: the IFMIF-DONES Project, Nucl. Fusion 59 (2019), 065002, https://doi.org/10.1088/1741-4326/ab0d57.

[7] D. Bernardi, et al., The IFMIF-DONES project: design status and main achievements within the EUROfusion FP8 work programme, J. Fusion Energ 41 (2022) 24, https://doi.org/10.1007/s10894-022-00337-5.

[8] K. Masuda, et al., Commissioning of IFMIF prototype accelerator towards CW operation, in: in 31st Int. Linear Accelerator Conf. (LINAC2022), Liverpool, 2022.

[9] P. Mendez, et al., LIPAc RF power system: design and main practical implementation issues, Fusion Eng. Des. 165 (2021), 112226, https://doi.org/10.1016/j.fusengdes.2021.112226.

[10] M. Weber, et al., Functional overview of the RF power system for the LIPAc RFQ, IEEE Tran. Plasma Science 49 (9) (Sept. 2021) 2987–2996, https://doi.org/10.1109/TPS.2021.3102840.

[11] C. de la Morena, et al., Single-step port-reconfigurable cavity combiner with high efficiency, Nucl. Instrum. Methods Phys. Res. A 972 (Aug. 2020), 164108, https://doi.org/10.1016/j.nima.2020.164108.

[12] C. de la Morena, et al., First validation experiments of the prototype solid state RF system for IFMIF-DONES, Fusion Eng Des 168 (2021), 112396, https://doi.org/10.1016/j.fusengdes.2021.112396.

[13] E. Montesinos, CERN SPS RF SSPA, from design to operation, in: in 12th Continuous Wave and High Average Power RF Workshop (CWRF2022), Geneva, Switzerland, 12-14 Sept, 2022.

[14] J. Jacob, J.-.M. Mercier, M. Langlois, G. Gautier, 352.2MHz-150kW solid state amplifiers at the ESRF, in: Proc. of IPAC11, San Sebastián, Spain, 2011, pp. 71–73.

[15] T. Inagaki, H. Maesaka, T. Ohshima, T. Asaka, C. Kondo, Y. Ohashi, S. Sasaki, Upgrade status of the RF system for SPRING-8 storage ring, in: in 10th Continuous Wave and High Average Power RF Workshop (CWRF2018), Hsinchu, Taiwan, 2018.

[16] D. Horan, The advanced photon source 350MHz RF systems –27 years of operation and future plans, in: 12th Continuous Wave and High Average Power RF Workshop (CWRF2022), Geneva, Switzerland, 12-14 Sept, 2022.

[17] M. Gaudreau, D. Cope, E. Johnson, M. Kempkes, R. Simpson, N. Stuart, High efficiency high power resonant cavity amplifier for PIP-II, in: Proc. IPAC19, Melbourne, Australia, 2019, https://doi.org/10.18429/JACoW-IPAC2019-THPTS095.

[18] C. de la Morena, et al., Fully digital and white rabbit-synchronized low-level RF system for LIPAc, IEEE Trans. Nucl. Sci. 65 (1) (Jan. 2018) 514–522, https://doi.org/10.1109/TNS.2017.2780906.