Technical Note for Market Survey on Radio Frequency Power System Procurement

In preparation of Call for Tender

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1. Introduction to IFMIF/LIPAc, IFMIF-DONES and DEMO

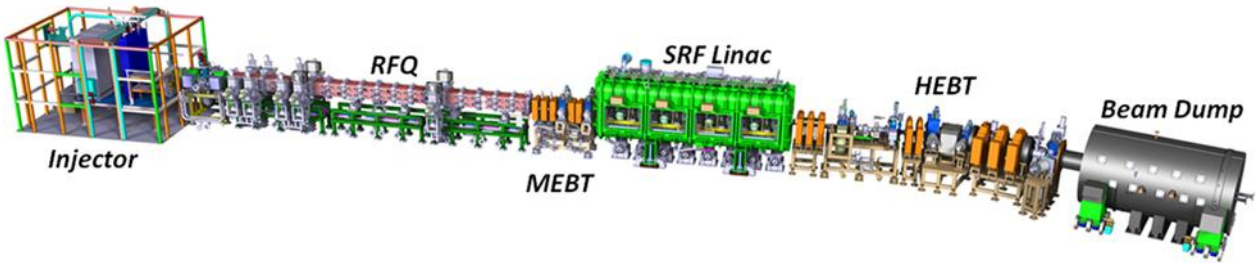
The European Joint Undertaking for ITER and the Development of Fusion Energy or 'Fusion for Energy' (F4E) is a type of European organization known as a Joint Undertaking created under the EURATOM Treaty by a decision of the Council of the European Union.
'Fusion for Energy' has three main objectives:

- Providing European contributions to the ITER international fusion energy research project being built in Cadarache, France.
- Providing European contributions to several joint projects with Japan that aim to accelerate the development of fusion - the "Broader Approach".
- Coordinating a programme of activities to prepare for the first demonstration fusion reactors that can generate electricity (DEMO).

The International Fusion Materials Irradiation Facility (IFMIF) aims to provide an accelerator-based, deuteron-lithium neutron source to produce high-energy neutrons at sufficient intensity and irradiation volume to simulate as closely as possible the first wall neutron spectrum of future nuclear fusion reactors such as DEMO and Power Plants. Under the framework of the Broader Approach (BA) agreement, the Linear IFMIF Prototype Accelerator (LIPAc, see Figure 1a) is being assembled and commissioned at the Rokkasho site (Japan) with the aim to develop and validate prototypes of the building blocks for the IFMIF accelerator system. The goal is to achieve continuous wave operation of a high current beam of 5-MeV deuterons to demonstrate the technological feasibility of the project.

European Designated Institutes of the National Governments committed as Voluntary Contributors to the projects have designed, manufactured and tested most of the components that make up the LIPAc facility. F4E is the Implementing Agency for the European contributions whereas the National Institutes for Quantum Science and Technology (QST) is the Implementing Agency for Japan.

a) LIPAc



b) IFMIF-DONES

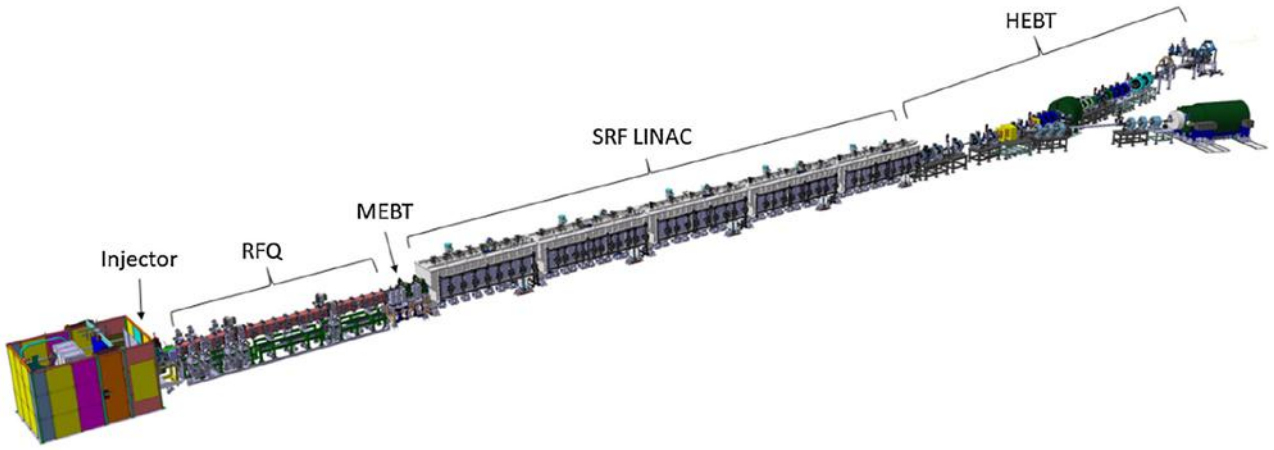


Figure 1: a) LIPAc and b) DONES accelerator subsystem layouts

Based on LIPAc, **the DEMO Oriented Neutron Source (IFMIF-DONES)**, under construction in Escúzar, Granada (Spain), will integrate the three main systems of the future IFMIF facility – the accelerator, the lithium target, and the materials test systems – and will accelerate deuterons up to 40 MeV to generate a high-intensity neutron flux to test and qualify materials for DEMO and future fusion power plants. DONES is therefore a key facility in the fusion roadmap, bridging technology validation and material qualification.

As a user facility, during its 30 years lifetime, **IFMIF-DONES facility is expected to achieve a** high **inherent availability of 70%** – which translated to the Accelerator Systems corresponds to an **inherent availability of 87%.**

As of the writing of this document, it is a joint project between Spain, the European Union, Japan and Croatia.

Fusion for Energy is leading the **European Union contribution** to the DONES Programme.

2. Description of IFMIF-DONES Radio Frequency Power System (RFPS)

The Radiofrequency (RF) Power System is the system in charge to generate, amplify, manage and deliver the required high power RF signal to the Accelerator Systems (AS) radiofrequency cavities (the Radiofrequency Quadrupole cavity (RFQ), the re-buncher cavities of the Medium Energy Beam Transport line (MEBT) and the Half-Wave Resonator (HWR) cavities of the Superconducting Radiofrequency (SRF) Linear Accelerator (LINAC)).

The characteristics and quality of this RF signal is a key parameter 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 (see **Figure 2**).

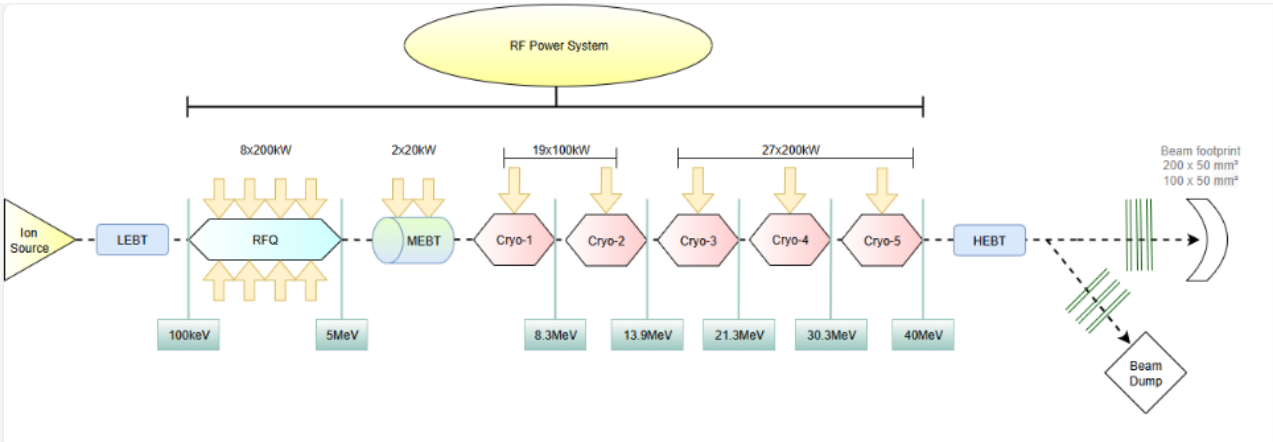


Figure 2: IFMIF-DONES Accelerator Systems Schematic

The RFPS is also in charge to react 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.

a. RFPS technical description

The RF Power System (RFPS) is composed of seven RF Blocks, each **comprising a set of RF Stations** dedicated to delivering the required RF power to their associated accelerator cavity or cavities. **In total, the RFPS includes 56 RF Stations together with the RF Local Instrumentation and Control Subsystem (LICS).**

The RF LICS integrates, among other devices, **the Low-Level RF (LLRF),** which **generates** the **175 MHz RF drive signal**, distributes **synchronous equal-amplitude and equal-phase signals to all amplifier modules, and implements the feedback loops for cavity field amplitude and phase stabilization**, ensuring the required beam quality. In addition, the RF LICS manages interlocks, RF conditioning, diagnostics, and fault recovery, while interfacing with the Central Control & Instrumentation Systems: with **CODAC** for supervision, synchronization, data handling, and software management; with the **Machine Protection Subsystem** for immediate shutdown of RF power injection in case of anomalies to ensure machine protection; and with the **Safety Control Subsystem** to guarantee immediate RF injection shutdown under unsafe conditions, including personnel access to restricted areas.

To ensure that the **complete RF Power System can be integrated within the allocated RF Room envelope**, each RF Station shall be designed around a main **RF Power Rack whose structural assembly fits within a maximum equipment footprint of 3 m (W) × 3 m (H) × 1.5 m (D).**

This footprint refers exclusively to the main RF Power Rack containing the RF amplifiers and associated internal subsystems. It excludes any optional external units that may be required in the final design (e.g., RF combination systems such as hybrid couplers and loads, or high-power circulator-based protection systems and their associated loads and supports) **and therefore does not account for any additional space those units might require.**

In addition to the RF Power Rack, the RF Power System also requires the Local Instrumentation and Control System (LICS) to be installed within the RF Area. The final design may therefore include a dedicated LICS Control Rack or equivalent cubicle. These unit**s shall fit within a maximum equipment footprint of 0.6 m (W) × 2 m (H) × 0.5 m (D).**

Furthermore, **sufficient free space shall be reserved around each RF Station** to ensure safe access, handling, and maintenance operations. A clearance of **more than 1.5 m around the equipment** is required to enable the movement and operation of handling tools, lifting devices, or transport carts used for coaxial lines and RF components**,** as visually described in **Figure 3.**

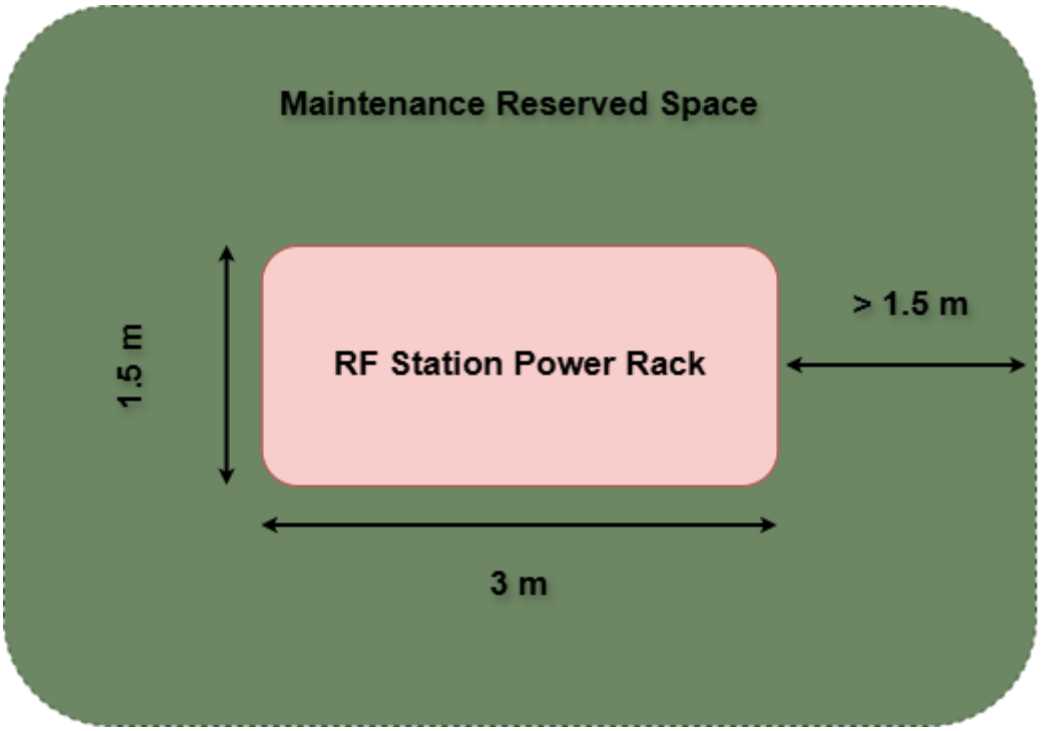


Figure 3. RF Station general layout.

The coaxial transmission lines provide the RF connection between the RF Stations and the cavity power couplers. Their design **is based on EIA-standard coaxial components**, with the diameter of each line selected **according to the RF power level required by the cavity.**

Table 1 provides an overview of the seven RF Blocks, indicating the number of RF Stations in each and the standard of the transmission lines used to deliver RF power to the cavities through their corresponding cavity power couplers.

RF Block	Number of RF Stations	Coaxial line Standard
RFQ Block	8	EIA 9 3/16”
MEBT Block	2	EIA 3 1/8”
Cryo-1 Block	8	EIA 6 1/8”
Cryo-2 Block	11	
Cryo-3 Block	9	EIA 9 3/16”
Cryo-4 Block	9	
Cryo-5 Block	9	

Table 1. RF Station distribution in each RF Block.

With respect to the RF power delivered to the cavity power couplers, three different power levels are defined:

1. **Nominal Output Power:** It is the minimum RF power that shall be delivered to the cavity power couplers to ensure that, considering the power dissipated on the cavity walls and the power transferred to the beam for its acceleration, the required RF power effectively reaches the cavity to generate the proper accelerating electric field. This value includes an appropriate margin to compensate for detuning effects, quality factor variations, transmission losses, and other operational uncertainties.

2. **Average Output Power:** Taking the nominal power as a reference, the average power corresponds to the additional RF power that the RF stations can provide under steady-state conditions. This additional margin is intended to compensate for power reductions or temporary underperformance in other RF chains, thereby maintaining stable cavity power and accelerating field.

3. **Peak Output Power:** The peak power refers to the transient power level occurring during the cavity filling process when RF power is first injected into a resonant cavity. It represents the highest instantaneous power value among the three defined levels.

Table 2, Table 3 and Table 4 describe the main particular characteristics that each RF Station must meet, appart from the general ones in **Table 5**.

Parameter	Value
Nominal Output Power (CW)	180 kW
Peak Output Power at Saturation	220 kW
Average Output Power at Saturation	200 kW
VSWR Ruggedness (CW)	2.3 (Return Losses ~ -8.1 dB)
Maintained Peak Reflected Power (~400% of maximum nominal power)	> 10 µs (No damage in the RF Chain)

Table 2. Each RFQ RF Station RF requirements

Parameter	Value
Nominal Output Power (CW)	8 kW
Peak Output Power at Saturation	16 kW
Average Output Power at Saturation	14 kW
VSWR Ruggedness (CW)	Total reflected @ any phase

Table 3. Each MEBT RF Station RF requirements

Parameter	Value
Cryo-1 & Cryo-2	
Nominal Output Power (CW)	105 kW
Peak Output Power at Saturation	130 kW
Average Output Power at Saturation	120 kW
VSWR Ruggedness (CW)	Total reflected @ any phase
Maintained Peak Reflected Power (~400% of maximum nominal power)	> 160 µs (No damage in the RF Chain)

Cryo-3, Cryo-4 & Cryo-5	
Nominal Output Power (CW)	180 kW
Peak Output Power at Saturation	220 kW
Average Output Power at Saturation	200 kW
VSWR Ruggedness (CW)	Total reflected @ any phase
Maintained Peak Reflected Power (~400% of maximum nominal power)	> 160 µs (No damage in the RF Chain)

Table 4. Each Cryo-1, Cryo-2, Cryo-3, Cryo-4 and Cryo-5 RF Station RF requirements

b. RF Power System key parameters

Parameter	Value
Radio Frequency	
Nominal Frequency	175 MHz
Bandwidth at 1 dB (centered at 175 MHz)	± 300 kHz
Gain Compression at Average Output Power	< 1 dB
Gain Static Stability not considering LLRF	< 0.3 dB
Phase Static Stability not considering LLRF	< ± 0.3 º
AC to RF Conversion Efficiency	> 60%
Harmonic Content Up to Nominal Power	< -30 dBc
RF Spurious	< - 60 dBc
Each RF Station availability	99.96%
RF Interlock[1] Reaction Time	< 5µs
Low-Level RF	
Maximum Frequency Shift	± 300 kHz
Phase Stability (After thermal stabilization)	< 0.25º RMS
Gain Stability (After thermal stabilization)	< 0.25% RMS
Beam-Loading Frequency Shift	<= 100 kHz
Amplitude Loop	< 0.5% RMS Resolution
	> 50kHz Bandwidth
	30 dB Dynamic Range
Phase Loop	< 0.5º RMS Resolution
	> 50kHz Bandwidth
	360º Dynamic Range
Tuning	< ± 1º Resolution
	>= 1 kHz Bandwidth
	>= ± 75º Dynamic Range
Operating Modes	Continuous Wave
	Pulsed (Conditioning and Commissioning) [**Table 6**]
Electrical Network	
Harmonic current	Total Harmonic Distortion: < 3%
	3rd Harmonic: < 1%
	5th Harmonic: < 0.9%

[1] **Including detection, internal processing, command transmission, actuator activation, and RF power cut-off.**

	7^{th} Harmonic: < 0.4 %
	> 7^{th} Harmonic: < 2%
Each RF Station Power Factor	> 0.99

Table 5. General RF Power System main parameters

The nominal operation mode of the IFMIF-DONES particle accelerator is in continuous wave (CW), so the RF Power System nominal operation is also in CW. However, the commissioning and conditioning phases of the accelerator require an exhaustive use of pulsed modes, so the RF Power System is designed to provide a wide range of pulse parameters (see Table 6).

Parameter	Value
Maximum Pulse Width	1 s
Minimum Pulse Width	10 µs
Minimum Repetition Rate	1 Hz
Maximum Repetition Rate	1 kHz
Minimum Duty Cycle	0.001%

Table 6: Pulsed Mode RFPS Main Parameters

In **full reflection** scenario, the reflected power can transiently reach levels significantly higher than the rated output power (as described in **Table 2** and **Table 4**) the **RFPS design shall demonstrate sufficient robustness to withstand such reflections during that required time.**

3. Scope of the future Call for Tender

The provisional scope of the contract includes the following **hardware deliverables**:

- 56 RF Stations including amplifier racks, control racks, solid-state modules, power combiners, reflected power protection.
- Ports and connectors within the RF Station required to properly interface with main building, cooling, electrical and control systems.
- RF output interfaces, including all coaxial components from the RF Station up to the cavity power coupler (elbows, flexible joints, rigid lines…), compatible with EIA-standard coaxial connections.

The provisional scope of the contract includes the following **activities**:

- Review and optimization of the reference RFPS design, including power combining and protection strategy (up to 400% reflected power) with an AC to RF efficiency > 60%.
- Manufacturing design and preparation – including, if required, the production of prototypes and mock-ups to validate and qualify the proposed design and the manufacturing process.
- Detailed engineering, safety analyses, RAMI optimization, and QA/QC planning.
- Definition of preventive and corrective maintenance strategy, including amplifier module replacement procedures.
- Provision of sufficient spare units to guarantee the contractual availability target over 10 years.
- For each phase of the system lifecycle within the scope of the supply: preparation and production of detailed documentation and exhaustive data packages for review and acceptance with the participation of experts from F4E, IFMIF-DONES and external experts.
- Procurement, manufacturing, and assembly of all components and subsystems of the RF Power System (RFPS), including (but not limited to):
    - Solid-state amplifier modules and associated power supplies.
    - Control and protection system.
    - Power racks and cooling infrastructure (forced-air, water-cooled…).
    - Control racks and cooling infrastructure (forced-air, water-cooled…), if needed.
    - RF Power combining and distribution components (coaxial combiners, hybrids couplers…).
    - Mechanical structures, cabling and auxiliary equipment required for full system operation.
- Series production of validated design.
- Factory Acceptance Tests (FAT) to demonstrate full functionality, including RF characterization (gain, bandwidth, stability, harmonics, spurious, linearity), efficiency measurement, and verification of interlocks and fault protection under representative load conditions.
- Shipment, delivery, and on-site installation, integration, and commissioning at the IFMIF-DONES Facility (Escúzar, Granada, Spain), including:
    - Transport and delivery of the 56 RF Stations and components to site.
    - Mechanical and electrical installation of the 56 RF Stations in the RF Area.
    - Integration with facility services (cooling, electrical power…).
- Site Acceptance Tests (SAT) after delivery and installation, including:
    - High-power verification at nominal frequency and output power, sustained for ≥ 2 hours under matched-load conditions.
    - Validation of Continuous Wave (CW), full-reflection and Standing-Wave (SW) operation.
    - Provide all required hardware, auxiliary devices and tools (e.g. high-power loads, phase shifters…).

The activities mentioned in the list above **shall be implemented according to a strict and high-standard Project and Quality Management Plan (PQMP).**

4. Technical and Industrial Capacity

This section lists the main operational requirements and performance targets to be achieved by the RF Power System (RFPS) for IFMIF-DONES.

We acknowledge that some of these requirements may specify operational values (e.g., power levels, operation frequency…) **that potential suppliers may not have previously implemented in full**. However, **this does not constitute an exclusion criterion for participation in the future Call for Tender**. Instead, dedicated questions have been included in the present Market Survey questionnaire to capture the suppliers' experience in related domains, which will be duly considered in the evaluation process.

The potential supplier is expected to have demonstrated experience in:

- **Design, manufacturing, and assembly of high-power solid-state RF amplifier systems in the range of 100kW to 250kW at >100MHz in Continuous Wave (CW) and pulsed mode**, with advanced power combining architectures and efficient thermal management strategies.
- **Development and implementation of RF power combining and distribution architectures with robust protection against extreme reflected power conditions.**
- **Capability to scale production capacity and sustain a series manufacturing pace,** ensuring on-time delivery of all RF Stations in accordance with the DONES project schedule (**delivery time** for all RF Stations over **4 years**). This includes the ability to manufacture and test multiple units in parallel while maintaining full QA/QC compliance.
- **Manufacturing engineering, quality assurance and control (QA/QC), documentation traceability, and compliance with standards applicable to nuclear or high-reliability scientific facilities** (e.g., ISO, IEC, EMC, electrical safety).
- **Execution of Acceptance Tests with dedicated high-power RF test stands, covering full RF characterization under CW, pulsed, full reflection and standing-wave operation** (gain, stability, harmonics, spurious, linearity, interlocks, thermal cycling) **including use of dedicated devices** (e.g., phase shifters or mismatched loads) for validation.
- **Delivery, on-site installation and commissioning of similar high-power RF systems for accelerator or scientific facilities**, including project management and coordination with multidisciplinary teams.

5. Market Survey

To establish an optimum contract strategy, F4E needs to develop its understanding of the market with a comprehensive list of possible interested EU suppliers.

In the frame of the Market Survey, interested suppliers are invited to submit the requested information. This information will be visible to F4E only and will not be communicated to other parties, except if agreed upon by the respondent(s).

Please answer to the F4E Market Survey by clicking on this LINK

This Technical Note is for information purposes. The corresponding Market Survey is carried out for information purposes only, in accordance with Fusion for Energy's Financial Regulation.

Participants/respondents in this Market Survey acknowledge that by replying to this Market Survey imposes no obligation on Fusion for Energy to a future procurement procedure. Submission of the survey does not imply the right to be informed of, or participate in, any procurement procedure launched by Fusion for Energy.

Based on the responses received, F4E may contact, and visit interested companies/entities to further explore the market and technical conditions of this development.