ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-MOD1

DEVELOPMENT OF DEUTERIUM-DEUTERIUM COMPACT NEUTRON SOURCE

A. Pérez[*,1], V. Etxebarria[1], I. Arredondo[1], J. Portilla[1], Javier Praena[2], A. Roldán[3], J.Feuchtwanger[1]
[1]Department of Electricity and Electronics, University of the Basque Country, Leioa, Spain
[2]Department of Atomic, Molecular and Nuclear Physics, University of Granada, Granada, Spain
[3]Department of Electronics and Computer Technology, University of Granada, Granada, Spain

Abstract

In the present work, we will present the status of the deuterium-deuterium (D-D) neutron source that is being developed in collaboration between the University of Granada and the University of the Basque Country. Our neutron source consists of an Electron Cyclotron Resonance (ECR) ion source which accelerates a deuteron beam towards a deuterated target. The ionization to achieve the deuterium plasma is achieved by radiating the cylindrical ERC plasma chamber with a magnetron 2.45 GHz signal and an 875 G magnetic field generated by 6 NdFeB magnets located around the plasma chamber. Moreover, a cylindrical alumina Radio Frequency (RF) window is used to keep the vacuum status from the ambient pressure condition inside the WR340 and helping the plasma to ignite. Once the plasma is generated, the deuterons are extracted from the plasma chamber using a Pierce electrode geometry and three other electrostatic lenses, fixed to different negative potentials. The beam is accelerated towards the copper target disk with a deuterated titanium mesh fixed to –100 kV which generates the desired neutron radiation. There are several applications of D-D neutron sources across scientific and industrial domains. In case of the University of Granada and its deep relation with the IFMIF-DONES neutron source, it is worth to mention that we plan to carry out experiments for determining the cross-sections of relevant isotopes in the studies of IFMIF-DONES for a better simulation of the behaviour of such material under high neutron flux irradiation.

INTRODUCTION

A deuterium-deuterium (D-D) compact neutron source is being developed in collaboration of the University of the Basque Country and the University of Granada. The main goal of this project is to gain scientific and engineering know-how on this type of source. The source will be based on the D-D fusion reaction described as $^{2}H(d,n)^{3}He$ [1-2]]. By colliding with deuterium positive ions, known as deuterons, a 3.27 MeV reaction is generated, where 2.45 MeV corresponds to a neutron and the other 0.82 MeV corresponds to a nucleus of ^{3}He. The full 3D design of the neutron source can be seen in Figure 1. First, the radio frequency (RF) subsystem where a high-power RF signal is generated and transmitted toward the plasma chamber. This Rf signal combined to a proper magnetic field generates an electron cyclotron resonance (ECR) deuterium plasma formed of deuterons. As these deuterons have a positive charge, fixing the target to a negative potential will extract them from the plasma chamber and accelerate them towards it. The target is deuterated, so as the ion beam impacts the target the D-D reaction is going to be produced and 10^7 neutron flux will be generated [3-4].

This paper is organized in the following way. Each section will describe a different subsystem of the D-D source. Moreover, the actual state of the project will be described with the conclusions. Finally, the future works are given.

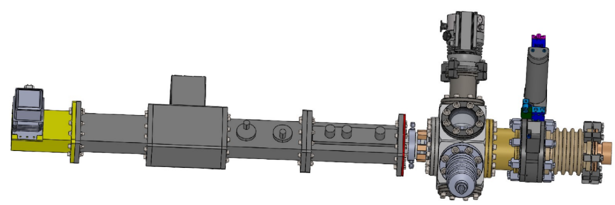

Figure 1: D-D source full 3D model design.

RF DESIGN

As stated in the previous section, an RF signal is needed to ionize the deuterium inside the plasma chamber. This RF signal is generated using a high-power magnetron able to achieve 1.3 kW of power with a frequency of 2.45 GHz. Once the RF wave is generated it needs to be transmitted towards the plasma chamber. A rectangular waveguide chain has been designed for this purpose, using the WR340 standard, which has an operating bandwidth from 2.2 GHz to 3.3 GHz. Following the magnetron an adaptor from magnetron to WR340 is used to optimize the power coupling from the RF source to the rest of the system. Then, a 3 kW water-cooled isolator has been implemented to avoid damaging the magnetron with the reflected power coming from the plasma chamber. Moreover, a directional coupler has been added to the design to monitor both forward and reflected power to the plasma chamber. Finally, a 3 manual probe tuner is used to modify the impedance of the WR340 system. When plasma is ignited, the impedance seen from the WR340 system towards the plasma chamber changes, and this will lead to worse RF coupling. Varying the position of the manual probes and monitoring the reflected power from the directional coupler, the impedance from the WR340 system can be modified to adapt it to the one in the plasma chamber. By doing so, the RF coupling will improve so with less RF power higher ion fractioned plasmas will be achieved.

* andoni.perezs@ehu.eus

ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-MOD1

PLASMA CHAMBER

In the design of our D-D source, is in the plasma chamber where the deuterons are generated. For this purpose, an ECR plasma is ignited from deuterium by ionizing it with a 2.45 GHz RF signal and fixing a magnetic field around the chamber. In order to have an ECR plasma the RF signal's frequency and the magnetic field follow the relationship stated in Eq. (1). Being q the electron charge in C, B the value of the magnetic field in T, and m_e the electron mass in kg.

$$f = \frac{q \cdot B}{2\pi \cdot m_e} \text{(Hz)} \tag{1}$$

Electromagnetic Simulation

As the plasma chamber has a cylindrical shape, with a radius of 20 mm and a length of 50 mm, an iris has been designed to adapt the impedance of the chamber and the one of the previous WR340 RF chain. Moreover, the RF subsystem works at ambient pressure while the plasma chamber needs to be in vacuum conditions. Therefore, a system capable of adapting the impedance and keep the vacuum state inside the chamber is needed. As seen in Figure 2, two 30 mm diameter and 5 mm long iris have been designed which added to the 38 mm diameter and 13 mm long alumina disk in the middle of both iris, and the plasma chamber can adapt the RF signal coming from the magnetron. The RF characterization results for the whole plasma chamber geometry suggest the designed work as expected having $S_{11} = -9.23$ dB at a frequency of 2.446 GHz. Moreover, the results obtained for the S_{11} parameter with the CST software and characterization with a Vector Network Analyzer (VNA) only had a variation of 1 dB in magnitude and 10 MHz in frequency. The vacuum state is conserved by one face of the alumina disk and an O-ring being pushed by it. Furthermore, the alumina is not only used as an RF window to maintain the pressure inside the chamber but also to help the plasma ignition. When an RF signal goes through the alumina disk, excited electrons are pulled out from the ceramic material and contribute to the ionization of the desired gas.

Magnetic Design

On the other hand, a magnetic field needs to be induced inside the plasma chamber for an ECR plasma to ignite. In our case, for a 2.45 GHz signal the magnetic field needed is of 875 G, following Eq. (1). For this purpose, 6 NdFeB magnets with a dimension of 15 x 15 x 24 mm are located around the plasma chamber. These magnets were chosen for their low cost and appropriate properties for the magnetic field values wanted to achieve. Apart from the magnets, three iron disks are needed to support the magnets around the chamber and optimize the magnetic field values which are seen in Figure 3.

HV EXTRACTOR

Once the plasma is ignited the next step is to form the ion beam. For our D-D source, the beam will be formed by

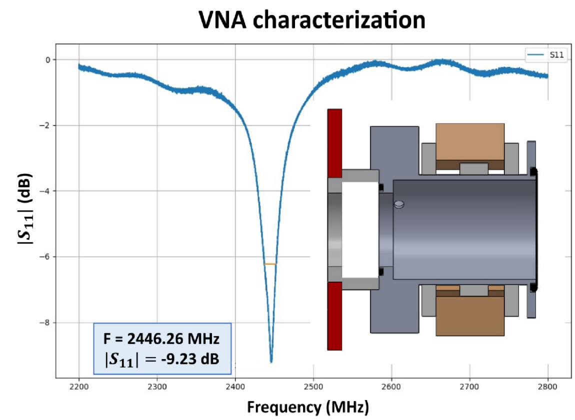

Figure 2: VNA S_{11} measurement and plasma chamber 3D model.

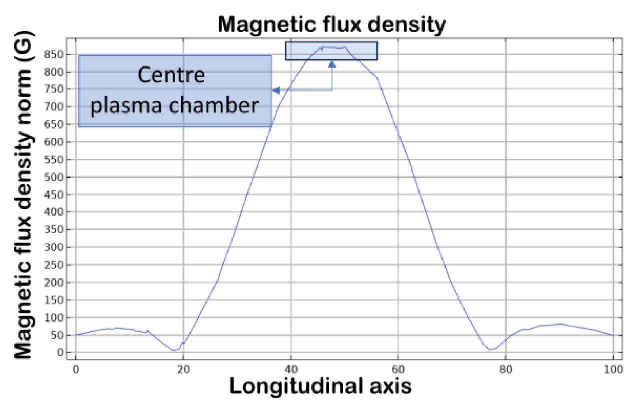

Figure 3: Magnetic field in the plasma chamber longitudinal axis.

deuterons, so it is a positive ion beam and negative potentials need to be fixed in order to accelerate and be able to extract the ions from the plasma.

Electrostatic Simulation

The ion beam extraction and acceleration will be achieved by fixing negative potentials to different electrodes. The number of electrodes, potential, and position are simulated in SIMION. The first electrode is the plasma electrode, which needs to have an angle of 67.5° to the beam axis (22.5° to the perpendicular). The shape of the electric field in the extraction gap will shape the beam as it is extracted so having this angle will produce an extraction field that has a zero transverse value at the edge of the beam, thus not having any focusing effect on the beam. This special shape is called pierce electrode geometry and will be fixed to the same potential as the plasma chamber, 0 V.

If the deuterated target is fixed to a negative potential the ion beam will be accelerated towards the target. Nevertheless, the beam will be highly focused on the center of the target, only using the 0,13 % of the target surface. A low dispersion of the beam around the target could lead to heating problems and waste of the target's deuterium. After the

ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-MOD1

first iterations, the addition of an electrostatic lens inside the vacuum chamber has proved to improve the dispersion of the beam towards the target. Having the target to -100 kV and the lens at -60 kV the beam impacts the 14.23 % of the target's surface. In the following iterations, the addition of more lenses will be studied.

Except for the target and the possible electrostatic lenses inside the vacuum chamber, the whole system is fixed to 0 V. To avoid HV discharges a PEEK tube will be used to isolate the high voltage from the target from the rest of the system. PEEK is a common material used for HV isolation for its high dielectric strength of 73 kV/mm.

TARGET

The target the deuteron beam will be accelerated towards consists of a metallic coin that has a titanium mesh with deuterium deposited in one of its faces. In this way, when the ion beam arrives, the deuterons impact the deposited deuterium and produce the $^2H(d,n)^3He$ reaction having the desired 2.45 MeV neutrons. As seen in Figure 4, the target will be mounted in a threaded system so it can be easily changed.

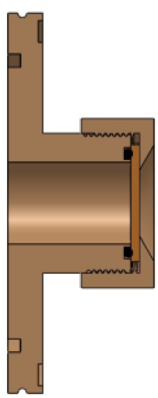

Figure 4: 3D target design.

ACTUAL STATE AND FUTURE WORKS

For the time this contribution is being written the RF system, plasma chamber and vacuum chamber have been implemented in the real-life design, Figure 5. At the moment the first deuterium plasmas are being ignited at low RF power, testing parameters such as the gas flow, temperature of critical components, or the forward and reflected power.

The remaining work can be divided into two groups: testing the already implemented parts and finishing the designing of the HV extractor and target to obtain neutrons. With the onsite parts, several testing will be done as in the RF part to obtain the minimum value of RF input necessary to ignite plasma. Currently, it is 100 W because it is the lowest RF power level the magnetron can provide. Moreover, adapt the impedance of the plasma chamber while plasma is ignited using the tuner so more power is coupled into the plasma chamber. Furthermore, Langmuir probe measurements will be performed to study the behaviour of the plasma that is being generated. On the other hand, the electrostatic simulations for beam extraction and the target for neutron generation will be executed. In order to implement the neutron generation, a radioprotection bunker needs to be build. The design of this bunker is being performed in the simulation software MCNP.

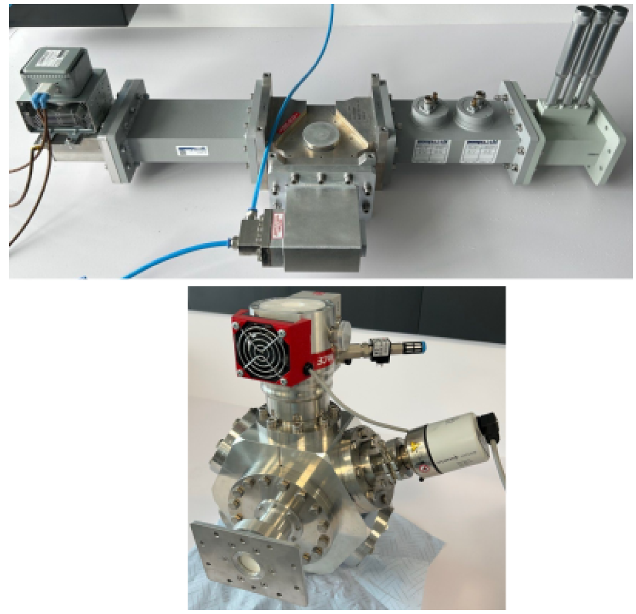

Figure 5: RF subsystem, plasma chamber, and vacuum chamber installed.

CONCLUSION

The magnetron and the WR340 chain have been fully tested with positive results. As mentioned in previous sections, the adaptation from WR340 to the plasma chamber geometry works as expected in the simulations as the magnets geometry do. The first tests to ignite plasma have started with promising results and the HV design process is coming to an end.

REFERENCES

[1] J. Csikai, Handbook of Fast Neutron Generators, CRC Press, 1987, ISBN: 0-8493-2967-1.

[2] Q. Ji, C.-J. Lin, C. Tindall, M. Garcia-Sciveres, T. Schenkel, and B. A. Ludewigt, "Note: Coincidence measurements of 3He and neutrons from a compact D-D neutron generator", *Rev. Sci. Instrum.*, vol. 88, no. 5, May 2017. doi:10.1063/1.4981896

[3] M. Fuller, M. Piestrup, C. Gary, J. Harris, G. Jones, J. Vainionpaa, D. Williams, J. Cremer, A. Bell, G. McRae, D. Faber, B. Ludewigt, J. Kwan, J. Reijonen, K.-N Leung, "Long-Lifetime High-Yield Neutron Generators using the DD reaction", Max 2009.

[4] Z.-W. Huang, J.-R. Wang, Z. Wei, X.-L. Lu, Z.-W. Ma, J.-L. Ran, Z.-M. Zhang, Z.-E. Yao, Y. Zhang, "Development of a compact D-D neutron generator", *Journal of Instrumentations*, vol. 13, January 2018. doi:10.1088/1748-0221/13/01/P01013