MICROWAVE INJECTION AND COUPLING OPTIMIZATION IN ECR AND MDIS ION SOURCES

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Abstract

The fundamental aspect of coupling between microwave and plasma of the Electron Cyclotron Resonance Ion Source (ECRIS) and Microwave Discharge Ion Source (MDIS) is hereinafter treated together with "ad hoc" microwave-based plasma diagnostics, as a key element for the next progress and variations with respect to the classical ECR heating mechanism. The future challenges for the production of higher-charge states, higher beam intensity, and high absolute ionization efficiency also demand for the exploration of new heating schemes and synergy between experiments and modeling. An overview concerning microwave transport and coupling issues in plasma-based ion sources for particle accelerator will be given in the paper, along with perspectives for the design of next generation sources.

INTRODUCTION

Electron cyclotron resonance ion sources (ECRISs) and Microwave Discharge Ion Sources (MDISs) are widely used nowadays in many acceleration facilities, for the productions of highly charged ions (HCIs) and of tens of mA of proton beams, respectively. In this paper we will focus on:

1. 2.45 GHz Radio frequency (RF) injection system design and measurements for the Proton Source of the European Spallation Source (PS-ESS) [1], currently under commissioning at INFN-LNS.

2. Modeling of wave-plasma interaction and test on the Flexible Pasma Trap (FPT) [2] and Plasma Reactor (PR), operating at the INFN-LNS, as test-benches for the investigation of innovative mechanisms of overdense plasmas heating and microwave-based diagnostics measurements [3].

RF MEASUREMENTS FOR PS-ESS

The detailed design and performances of 2.45 GHz Microwave Discharge Ion Sources, based on the principle of the off-resonance microwave discharge, are discussed in many references [4, 5]. Hereinafer we focus on the microwave injection system design and measurements of the PS-ESS source.

The microwave line, shown in Fig. 1, consists of:

1. Pulsed 2 kW 2.45 GHz Magnetron generator with continuous power supply on the filament to decrease the ripple, with external remote control of high and low level of the pulses, and On/Off duration time controlled by optical fiber. The emission head of the magnetron is protected from the reflected power by a RF circulator.

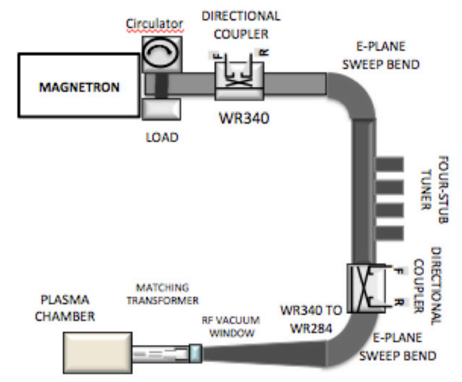

Figure 1: PS-ESS 2.45 GHz microwave injection block scheme.

2. Cross-Guide Directional Coupler for a simultaneous measure of forward (2 kW max) and reflected power at 2.45 GHz (Coupling coefficient= 40 dB and Directivity= 30 dB).

3. WR340 Waveguide 4-stub Automatic Tuning Unit (ATU): as soon as the generator delivers microwaves, the auto tuner matches instantaneously the load and maintains permanently the reflected power at a low level [6].

4. Broadwall Multi-hole Directional Coupler for a simultaneous measure of forward (2 kW max) and reflected power at 2.45 GHz in a WR340 waveguide (Coupling coefficient= 50 dB and Directivity=40 dB);

5. WR284 Waveguide quartz pressure window (Max. Power 2 kW Continuous Wave and VSWR<1.15 at 2.45 GHz).

6. WR284 waveguide multi-step binomial maximally flat matching transformer which permits a progressive match between the impedance of WR284 waveguide and the impedance of plasma filled chamber.

A waveguide transition WR340 - WR284, two WR340 90° E-plane bends and Diode RF Power probes with a measurement range from -57 dBm to +33 dBm at 10 MHz-18 GHz

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connected to the ports (N-connectors) of directional couplers, complete the microwave layout.

The use of directional couplers for incident and reflected power measurements placed in two parts of the microwave line (one immediately after the magnetron output and the other one just after the ATU) represents a very important microwave diagnostic tool providing information on the interaction between the electromagnetic waves and the plasma, which depends mainly on the plasma density and absorption efficiency of the energy carried by the microwave [7].

As a first step, we experimentally tested the microwave line in pulsed operation considering a waveguide matched load in place of the plasma chamber and by inserting an impedance tuner between the microwave generator and the matched load. A ripple measurement has been carried out on the output pulse from magnetron when the maximum power of 2 kW is applied on the waveguide matched load. In Fig. 2 the signal amplitude is around 200 mV which corresponds to 2 kW value. The signal ripple has an amplitude of about ± 1 mV (± 10 W). Therefore we can conclude that ripple is 1%.

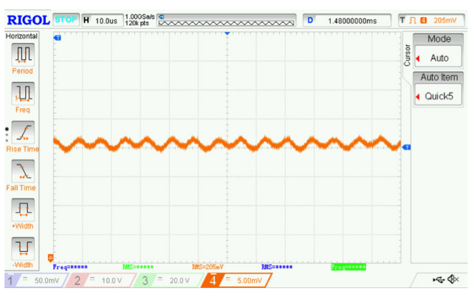

Figure 2: Ripple measurement of ± 0.5% (P_{FW}=2 kW)

During the PS-ESS conditioning, when the real plasma load is present, we acquired reflected and forward RF power from the RF power probes connected to the Broadwall Multi-hole Directional Coupler.

Figure 3 shows the plasma ability to absorb the incoming microwave power that is gradually increased from 20 W to 120 W in CW mode. After this value the plasma density is high enough to absorb more that 99.5 % of the injected power. Results show an optimum matching of power inside the plasma chamber that is very promising for the beam extraction process.

The software used for the data acquisition of the RF probes gives us also the possibility to extract the stability of the two measured power values. We select a data acquisition duration of 10 μs and an acquisition rate of 10 Hz; the standard deviation was calculated after 2000 counts. Figure 4 shows the fraction between the standard deviation and the adsorbed power (forward minus reflected) versus the forward power. The result shows that with an injected power greater that 120 W the plasma features a very stable condition with a fluctuation below 0.05%. We estimate that such a value will permit to reach the ±2% of beam stability, as requested by the ESS project.

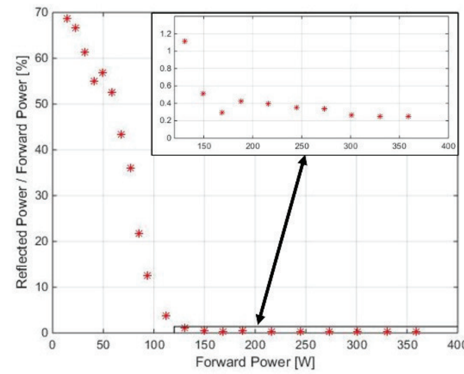

Figure 3: Fraction of reflected microwave power vs injected

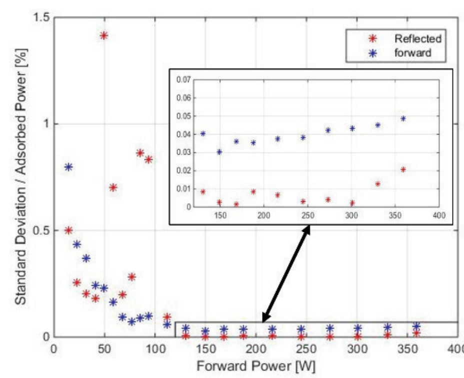

Figure 4: Stability of microwave absorbed power.

Finally we acquired forward and reflected power from power probes (which represent an useful RF diagnostic to retrieve plasma condition stability), in typical pulsed condition imposed from the external timing system (in optical fiber) with a pulse width of 6 ms, 14 Hz repetition rate, forward power P_{FW} = 400 W and gas flow rate= 1.41 sccm (Fig. 5): it is evident that the overall system is well-matched and that the ATU in automatic mode operation permits to find the optimum working point. If the gas flow rate is too low (under 1.01 sccm), the RF pulse becomes unstable.

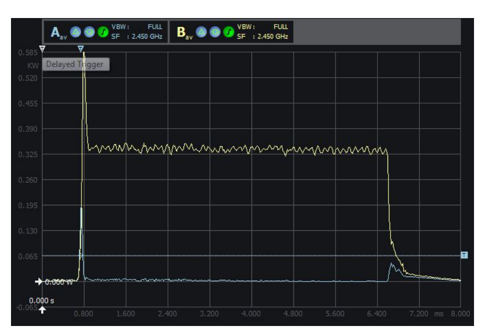

Figure 5: Forward power P_{FW} (yellow curve) and reflected Power P_{Refl} (blue curve) when the ATU is in automatic mode and gas flow rate is 1.41 sccm.

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RF MODELING AND EXPERIMENTAL RESULTS

Up to now in almost all operating ECRIS the increase of the electron density and extracted current is obtained through the increase of microwave frequency and confinement magnetic field. ECRIS devices are density limited, because the electromagnetic waves cannot propagate over the cut-off density. Many experiments, mainly based on slight variations of the microwave frequency (frequency tuning effect) and the use of two or more frequencies for plasma heating, have been carried out to verify the possibility to improve the plasma heating outside the framework traced by the Standard Model. An alternative to the classical ECR interaction is the electrostatic wave heating, driven by Bernstein waves. On the PR operating at INFN-LNS some evidences of Bernstein wave (BW) generation were observed in [8], obtained via the inner plasma Electromagnetic-to-Electrostatic wave conversion. Moreover a novel frequency-sweep microwave interferometry [3] enabled measuring the overall density of the whole plasma. The measurement of the line-integrated density $n_e = 2.1 \pm 1.0 \cdot 10^{18}$ m^{-3} for the PR demonstrates that the plasma density can be measured in a non-intrusive way also in compact ECRIS ans MDIS ion sources with the possibility to improve the tuning of existing sources in terms of magnetic trapping and RF coupling.

The need for a more flexible magnetic field and RF injection system suggested to design and develop a different type of ECRIS-like plasma trap, named FPT [2]. FPT can work with different plasma heating schemes by means of three different microwave systems, one parallel and two perpendicular with respect to the plasma chamber. The axial injection works at frequencies in the range of 4-7 GHz. A directional coupler enables the measure of forward and refected power, while an insulator safeguards the TWT by the reflected power. The innovative perpendicular microwave launcher [9] consists of an array of two waveguides properly phased in order to tilt the injection angle, which plays a key role for modal conversion from the BW generation. The contemporary use of the different microwave inputs on FPT allows operating with a double frequency (first and second harmonic) mode: a fraction of power provided to the plasma by means of the usual ECR-heating process by a standard double-ridge rectangular waveguide, while the additional RF power at the second harmonic is injected along the perpendicular direction with respect to the axis-symmetric magnetic field, in order to excite EBW through O-SX-B conversion mechanism.

CONCLUSION

The future challenges of higher-charge states and beam intensity, high-charge breeding efficiency, and high absolute ionization efficiency need the exploration of new heating schemes and synergy between experiments and modeling as described in this paper. The plasma conditioning phase on the MDIS-type source PS-ESS, started in July 2016: it has shown an excellent RF-plasma coupling, above 99.5%. Reflected power fluctuation below 0.05% was measured providing a great starting point to reach the beam stability requested by the ESS accelerator. The stability of the absorbed microwave power tells us the overall RF design (both in terms of launching and diagnostics) was successful. A deeper study of the mechanisms for overdense plasmas generation and to investigate new strategies for improve the plasma-wave coupling in ECRIS devices is ongoing on the FPT: the use of two perpendicular microwave injection lines at different frequencies enable exploring also the aspects of resonant absorption of waves energy by electrons at the second-harmonic of the cyclotron resonance.

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