Experimental investigation of RF driver equivalent impedance in the inductively coupled SPIDER ion source

Palak Jain, Mauro Recchia, Alberto Maistrello and Elena Gaio

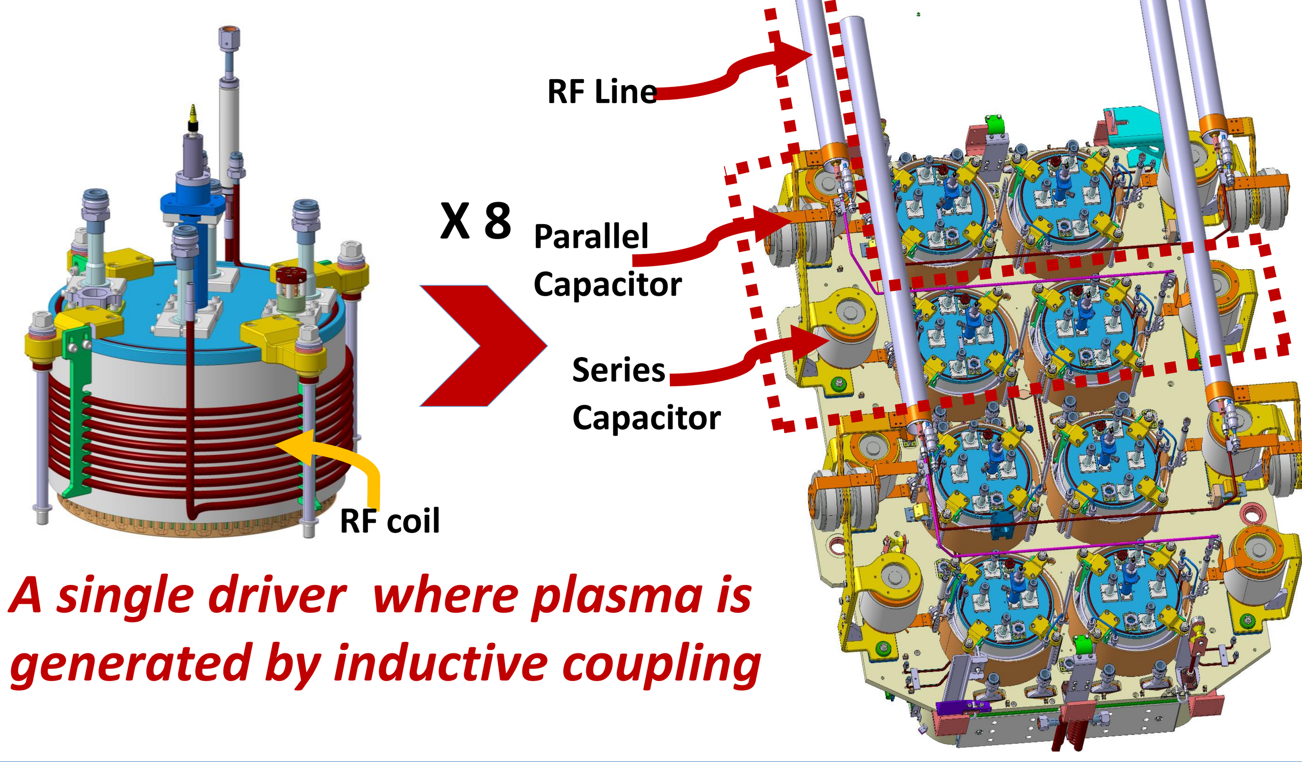
Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), Corso Stati Uniti 4, I-35127 Padova, Italy

Email: palak.jain@igi.cnr.it

International Conference on Ion Sources, September 20 – 24, 2021

Introduction

- SPIDER is the full scale prototype of the negative ion source of the ITER HNBI.
- Designed to achieve a beam current density of 355 A/m^2 of negative Hydrogen ions (285 A/m^2 with negative Deuterium ions) with 100 keV energy, for a beam duration of 3600 s.
- **Four independent RF circuits required to deliver a total power of 800 kW to the plasma. Each circuit is composed of an RF oscillator, a transmission line, L type matching network (composed of a parallel capacitor and two series capacitor) and two RF coil in series.**



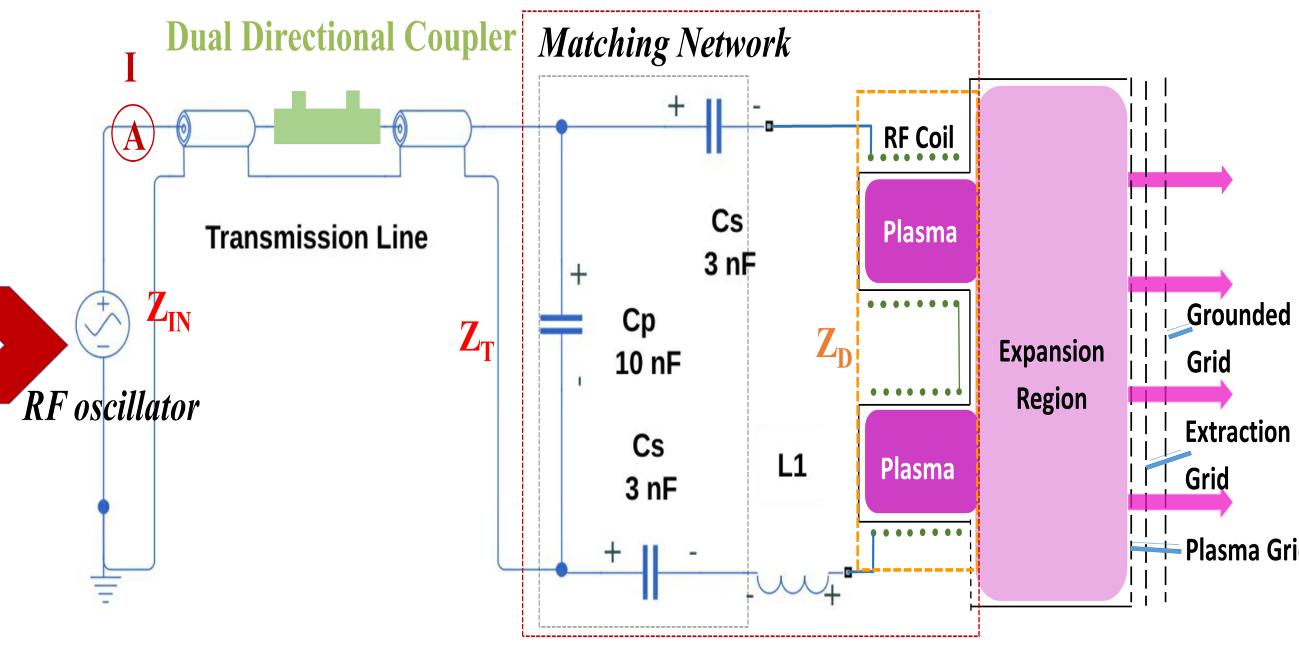
A single driver where plasma is generated by inductive coupling

Aim 1): To estimate the driver equivalent impedance

It is a complex task because a local measurement (on ion source) of the driver impedance in plasma operation is not possible.

Methodology Adopted: electrical measurements available at the output of RF oscillator and from dual directional coupler are used as an input to a suitable electric model for the RF circuit.

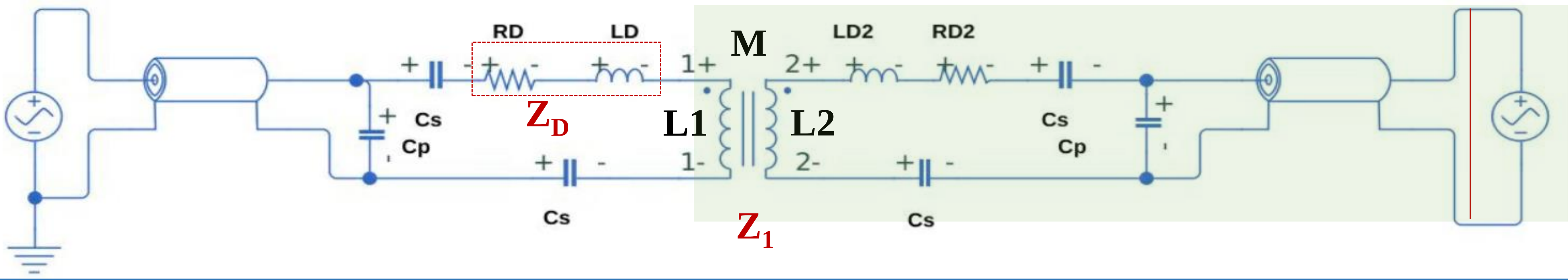
Motivation: It is a useful parameter for the estimation of electron density from the electrical measurements [1] and a key parameter for the estimation of the power transfer efficiency to the plasma [2].



Aim 2): Explore driver impedance variation in various experimental conditions, like RF power, gas pressure, PG current, type of gas, Cesium, etc.

Motivation: driver impedance is mutually coupled to the plasma which has a variable impedance depending on the experimental conditions. The knowledge of variation in driver equivalent impedance can lead to an accurate design of matching network which can allow to achieve transfer of full power to the driver.

Impact of Mutual Coupling between two RF circuits



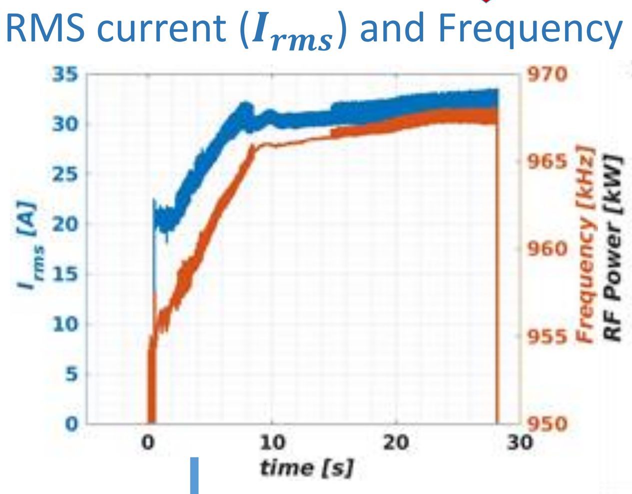
Mutual coupling ($\sim 0.1\ \mu H$) between the neighboring RF circuits due to the electrical connections ($\sim 1\ \mu H$ of inductance).

Analytically, the impact of mutually coupling on driver impedance Z_D is found to be negligible (< 5 %) assuming 5 Ω and 20 µH for drivers resistance and inductance with plasma. Therefore, only a single RF circuit has been considered!

Methodology: Electrical Measurements + Model

RF oscillator's output

RMS current (I_{rms}) and Frequency (f)

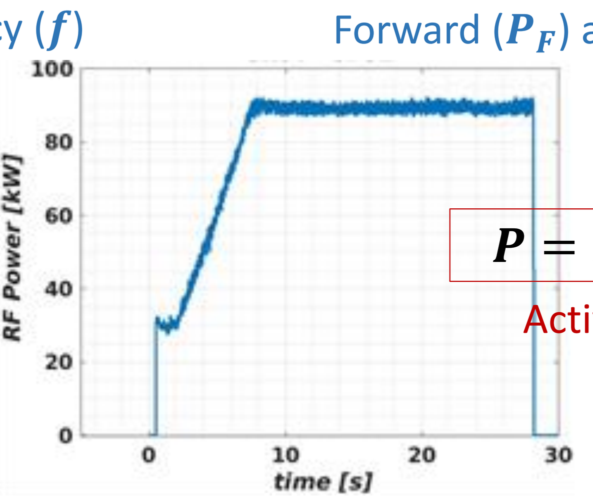


$$real(Z_{in}) = \frac{P}{I_{rms}^2}$$

At Oscillator's output

Dual Directional Coupler

Forward (P_F) and Reflected (P_R) Power



$$P = P_F - P_R$$

Active Power

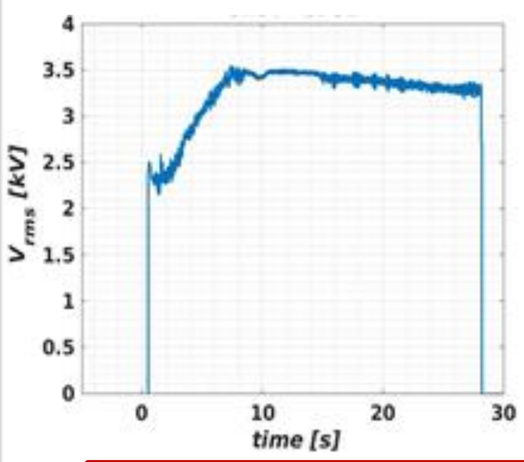
$$|\rho| = \sqrt{\frac{P_R}{P_F}}$$

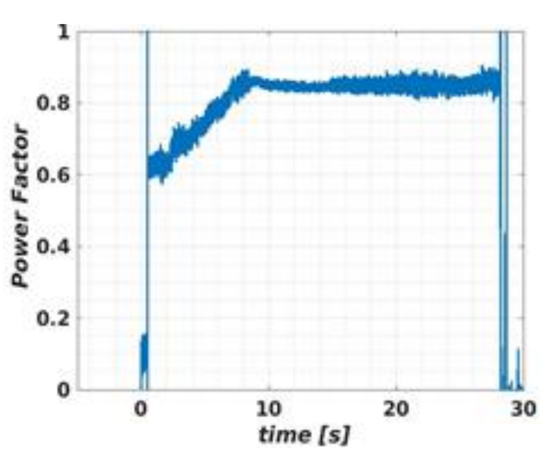
Reflection Coefficient

$$|Z_{in}| = \sqrt{\frac{(Z_0^2 * (1 - |\rho|^2)) - 2Z_0 * real(Z_{in}) * (1 + |\rho|^2)}{|\rho|^2 - 1}}$$

RMS Voltage — *Power Factor*

$$Z_{in} = |Z_{in}| e^{i\varphi} \qquad V_{rms} = \frac{P}{I_{rms}\cos(\varphi)} \qquad \cos(\varphi) = \frac{real(Z_{in})}{|Z_{in}|}$$





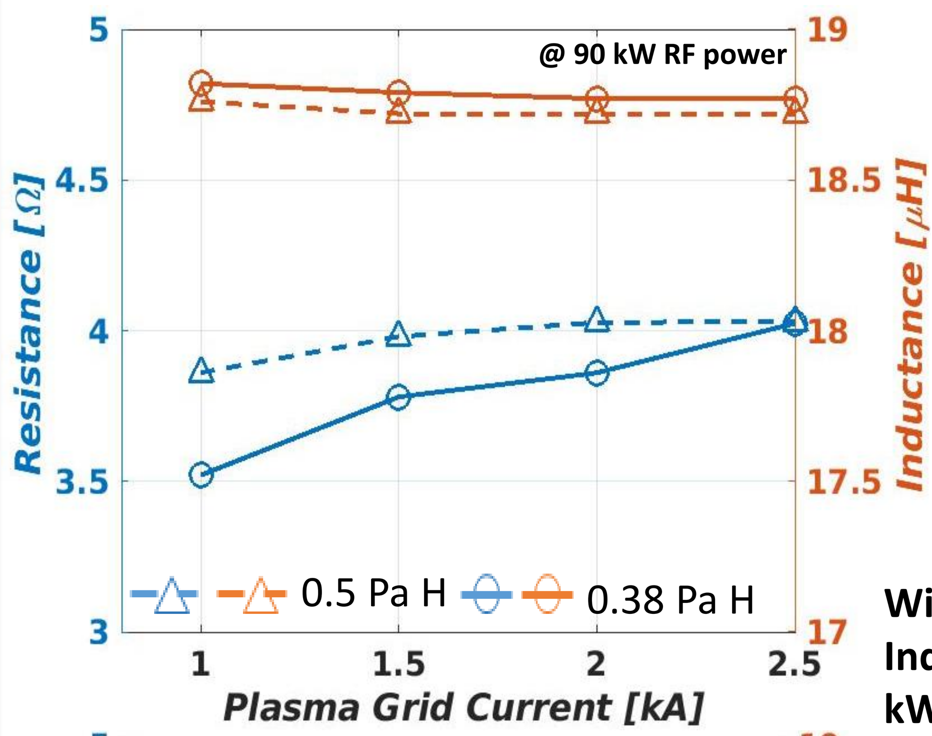
$$Z_T = \frac{Z_{in} - Z_0 \tanh(i\omega l\sqrt{LC})}{1 - \frac{Z_{in}}{Z_0}\tanh(i\omega l\sqrt{LC})}$$

At transmission line output

$$Z_D = \frac{Z_T\left(\frac{1}{j\omega C_p}\right)}{\left(\frac{1}{j\omega C_p}\right) - Z_T} - \frac{1}{j\omega C_s} - j\omega L_1 = R_D + j\omega L_D$$

Impedance of two driver in series

Results (for the driver pair mounted on segment 2)

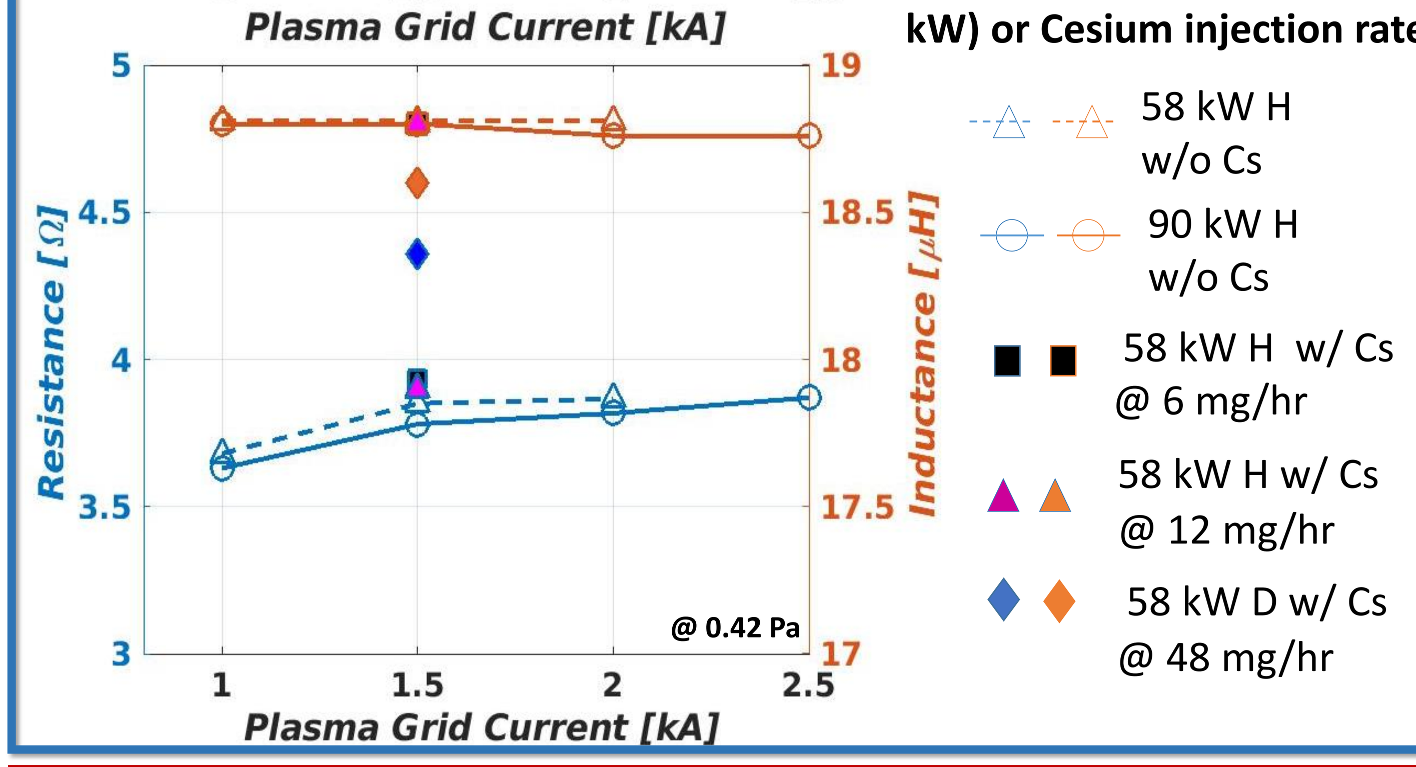


Without plasma, Resistance = 1.9 Ω and Inductance = 19.25 µH.

Resistance increases with the increase in gas pressure and Plasma Grid current due to the increase in electron density.

Inductance decreases slightly with the increase in gas pressure and Plasma Grid current due to the increase in electron density.

With Hydrogen: No change in Resistance and Inductance with the change in RF power (58 – 90 kW) or Cesium injection rate (0 – 12 mg/h)



Isotopic effect: At 58 kW RF power and 0.4 Pa gas pressure, in Deuterium, Resistance is higher than in Hydrogen and vice versa for Inductance

Summary and Future Work

Exploiting the measurements available from Dual Directional Coupler and a model for a single RF circuit, the results in terms of drivers equivalent impedance (resistance and inductance) under various experimental conditions of SPIDER have been presented.

In future, an extensive analysis can be provided for all 4 RF circuits in a wider (available) experimental conditions.

References

[1] M. Bandyopadhyay et al., doi: 10.1088/0029-5515/55/3/033017.

[2] M. Recchia et al., To be submitted to Plasma Source Science and Technology, 2021

Acknowledgements

This work has been carried out within the framework of the EUROfusion consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.