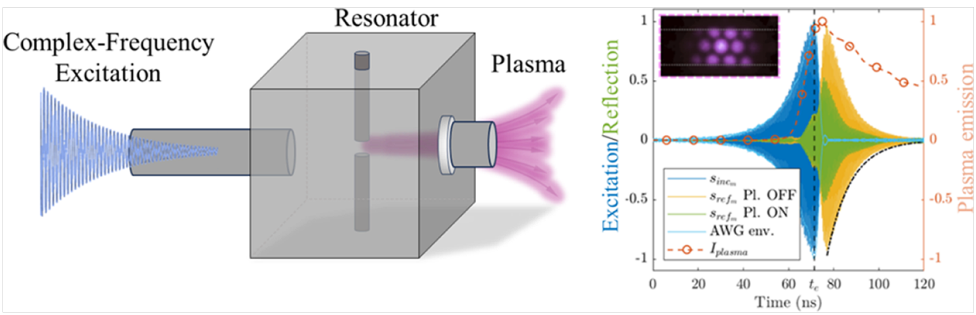
Reflectionless plasma ignition via virtual perfect absorption in a truncated waveguide

International collaboration France - USA

Context

This internship is part of a project recently launched in Toulouse to develop an innovative reflectionless plasma source [1]. Rather than adjusting the design of the system, this plasma source relies on the shaping of the wavefront of the incident microwave signal in order to optimize the efficiency of the plasma process by tailoring its dynamics. This can be done by incorporating an analysis of fundamental aspects of wave scattering. In this context, Virtual Perfect Absorption (VPA) has been introduced as a method allowing to perfectly capture light within a resonator [2]. Its principle consists in exciting a scattering matrix “zero” on the complex frequency plane. This mechanism maintains a critical coupling in resonators, requiring a balance between directly reflected waves and leakage waves. The “virtual” in VPA indicates that it stores the incident wave’s electromagnetic energy, in contrast with conventional absorbers, which convert this energy to other forms. In practice, it consists in sending an exponentially increasing signal to the cavity, thus cancelling the reflection during its excitation. VPA has been demonstrated in various systems and recently experimentally implemented in the microwave domain with exponentially increasing signal lasting a few tens of nanoseconds.



As illustrated on the figure above (taken from [1]), VPA has been shown to effectively ignite a plasma without reflection during the ignition stage [1]. The incident signal (blue) has enabled the ignition of a plasma (as shown by the emitted light intensity, in red) without reflection (green signal).

Motivations of the internship

The only demonstration of reflectionless plasma generation via VPA has been obtained with the resonant cavity of [1]. The aim of this internship is to explore another configuration: a waveguide structure, with a section that has different cross-sectional dimensions at its end. With VPA, we can perfectly absorb and store the incident wave for a desired time in a very small section of waveguide. The high intensity of the field obtained is thought to be able to generated a plasma. This seems pretty interesting, and would be the first demonstration of reflectionless plasma ignition in a waveguide structure.

Internship proposal

The main objective of this internship is to explore the possibility of using waveguide structure for reflectionless plasma ignition. To that end, the trainee will have to design and realize this waveguide, before trying to ignite plasma via VPA. Depending on the progress of the work and the trainee's preferences, a specific simulation code may also be developed. The internship is organized around three main stages:

- **Become familiar with theoretical concepts**

  − The trainee will have to familiarize himself with the concepts of VPA. For this, the trainee will benefit from the expertise of Alex Krasnok, one of the inventors of the VPA concept [2].

  − The trainee will have to familiarize himself with the concepts of reflectionless plasma ignition. For this, the trainee will benefit from the support of people in Toulouse (LAPLACE, ISAE-SUPAERO) who where the first to demonstrate reflectionless plasma ignition via VPA [1].

- **Realization of the experimental set-up**

  The trainee will have to design and build the waveguide structure. Then its electromagnetic behavior will be compared with the simulation results (simulations that have been done by Alex Krasnok). Finally, VPA will be experimentally demonstrated on this set-up.

- **Reflectionless plasma ignition by VPA in the realized device**

  − The experimental set-up will first be adapted to allow plasma ignition. To that end, a plasma tube will be incorporated to the device.

  − Then, the trainee will have to try to ignite a plasma via VPA with this set-up. To that end, the incident signal will be amplified by a high power amplifier. As in ref [1], a ICCD camera will be used to monitor plasma initiation. Hence, this first reflectionless plasma ignition on a waveguide structure will be characterized from an electromagnetic and plasma point of view.

– A specific numerical code could also be developed. It would be based on the numerical code we have developed in [3]. This code is a 2D FDTD (Finite Difference Time Domain) code, in which Maxwell's equations are coupled with a fluid description of the plasma [3]. It could be adapted to describe the reflectionless plasma ignition in the waveguide structure. Comparison with the experimental results will be made in this case.

– The last part consists in writing the internship report and possibility in publishing the results in a scientific journal, depending on the results obtained.

Informations

- Location: ISAE-SUPAERO (`https://www.isae-supaero.fr/en/`) and LAPLACE (`https://www.laplace.univ-tlse.fr/`) laboratories.
- Disciplines: electromagnetism, microwave plasma.
- Profile required: We are looking for a candidate with a Master's degree/engineering school background in microwave and/or plasma physics, with a particular interest in microwave-plasma interactions.
- Contacts :

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References

[1] Théo Delage, Jérôme Sokoloff, Olivier Pascal, Valentin Mazières, Alex Krasnok, and Thierry Callegari. Plasma Ignition via High-Power Virtual Perfect Absorption. *ACS Photonics*, 10(10):3781–3788, October 2023. Publisher: American Chemical Society.

[2] Denis G. Baranov, Alex Krasnok, and Andrea Alù. Coherent virtual absorption based on complex zero excitation for ideal light capturing. *Optica, OPTICA*, 4(12):1457–1461, December 2017. Publisher: Optica Publishing Group.

[3] V. Mazières, O. Pascal, R. Pascaud, L. Liard, S. Dap, R. Clergereaux, and J.-P. Boeuf. Space-Time Plasma-Steering Source: Control of Microwave Plasmas in Overmoded Cavities. *Phys. Rev. Appl.*, 16(5):054038, November 2021. Publisher: American Physical Society.