Investigation of Ion Bombardment Role on Radio-Frequency Arcs Ignition

Riccardo Casagrande[1,2,3,a)], Ferdinando Gasparini[3], Helmut Fünfgelder[2], Gerhard Siegl[2] and Jean-Marie Noterdaeme[1,2]

[1]*Department of Applied Physics, Ghent University, Belgium*
[2]*Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany*
[3]*Consorzio RFX, 35127 Padova, Italy*

[a)]Corresponding author: riccardo.casagrande@ipp.mpg.de

Abstract. One of the performance limiting factors in Ion Cyclotron Range of Frequencies (ICRF) systems for thermonuclear fusion reactors is the voltage holding capability of the launchers. Increased voltage stand-off, hence power density of ICRF launchers, would be a desirable feature for future fusion reactors. This contribution showcases the design of IBEX (ICRF Breakdown EXperiment), an experimental set-up for fundamental studies on Radio-Frequency vacuum arcs, with particular focus on the effect of an external plasma in the triggering mechanism. The experiment consists of a quarter-wavelength resonator, able to produce up to 43 kV RMS at 46 MHz. The device will be used for basic understanding of the arc mechanism in RF structures subjected to strong ion fluxes.

INTRODUCTION

Considering the ICRF system as a radiating resonant circuit, the power delivered to the plasma is proportional to the coupling resistance and the square of the maximum voltage on the resonant line. Power handling can thus be optimized by acting on the plasma density in front of the antenna, and on the voltage stand-off of the system.

To avoid breakdown in the antenna, ITER Organization specified a limit for the electric field along the magnetic field lines of 2 kV/mm, with a maximum voltage of 45 kV. With these limits, the cut-off layer needs to be moved closer to the antenna, to achieve relevant power coupling [1]. A higher plasma density in the vicinity of the first wall, on the other hand, can be detrimental in the long term for plasma facing components, and for the antenna voltage stand-off itself. In addition, previous experiments with a high voltage RF probe in Asdex Upgrade have identified the plasma eruptions during Edge Localized Modes (ELMs) as possible triggering events for arcing, and the ion current collected by the probe as a particularly sensitive parameter for arc ignition [2].

Increasing the coupling resistance through tailoring of the edge plasma density is a viable solution to optimise power handling, but this technique could encounter the limitation of acceptable heat fluxes to the first wall components. Thus, the square dependency of the voltage on the coupled power constitute in itself a sufficiently strong motive for the understanding of underlying arcing processes in ICRF antennas.

Hence, to pursue the investigation of fundamental mechanisms of high-voltage RF breakdown in a tokamak environment, with a view to improving the power handling, a compact quarter-wavelength resonator able to interface with other test facilities such as SIESTA [3] and IShTAR [4] has been developed.

VACUUM ARCS

Vacuum arcs need a source of electrons and neutrals in order to ignite. Free electrons in the cathode can overcome the potential barrier due to a reduction in the work function under high temperature or electric field. Field emission is the prevailing phenomenon close to high voltage nodes in a resonant system. The typical source of gas in vacuum arcs is field evaporation of cathode material, but in a tokamak environment a localized source of neutrals might come from a variety of other processes, including ion bombardment from a dense plasma diffusing inside the antenna box, or fast ion losses.

If the electrons emitted from the cathode gain enough energy in the accelerating field and the neutral density reaches a critical value, an extremely dense plasma (up to 10^{26} m^{-3}) builds up close to the surface [5]. Vacuum arcs typically evolve from a surface thermal instability, regulated by the rate of input and output energy at the field emitter. Once the dense plasma has formed, a thin sheath builds up close to the surface, thus enhancing the field emissions and neutral production, due to self sputtering. At this stage, the emitter is subject to several heating and cooling mechanisms: these are mainly Joule heating, ion bombardment heating and cooling by atom evaporation and electron emission. If the rate of energy input is much larger than the rate of heat removal, the emitting micro-tip will explode due to thermal runaway. In general, a limitation on the field emitted current density exists, for which explosive events happen on the cathode surface. This current density limit is in turn correlated to extremely high local electric fields (10 GV m^{-1}), at which several mechanisms of surface failure become relevant [6].

With ITER Organization imposed electric field limits, these breakdown triggering events would appear only with unrealistic field enhancement factors β of 5000. With a realistic $\beta = 200$, a plasma of density $n_e = 10^{19}$ m $^{-3}$ would be needed to increase the electric field up to limit values for breakdown, through the sheath space charge. The required density is several orders of magnitude larger than the scrape-off layer typical densities, and even during strong MHD activity such a dense plasma is not expected to reach the antenna straps. A more realistic hypothesis is that a low density plasma, with ω_{pi} comparable to the antenna operating frequency, penetrates the antenna box: electrons would be depleted quickly, while an ion space charge can be modulated by the antenna electric field, periodically enhancing the field emission current and bombarding the surface.

In addition to low density plasma diffusing into the antenna box, fast ions lost to the wall might play a role in arc ignition, or surface damage. Early arc experiments with a negatively biased electrode in argon plasma, showed a steep increase of arcing rate for ion power fluxes above 19 MW m^{-2} [7]. In tokamaks, ion fluxes to the first wall components can exceed the aforementioned value in the presence of ICRF heated discharges with large MHD activity. In Asdex Upgrade, fast ions heat fluxes up to 30 MW m^{-2} in the presence of a tearing mode have been measured on a fast ion loss detector positioned 5 cm from the separatrix [8].

Another important aspect on ignition of vacuum arcs is the surface condition. Presence of oxide layers, adsorbates and roughness of the surface can strongly affect the arc ignition. In particular, depending on the Fermi level of occupied states on the adsorbed atom, the work function can either increase or decrease. In tokamak operation with detached divertor or seeding for ELM mitigation, nitrogen monolayers can form on the antenna surfaces and affect the voltage stand-off.

The aim of this study is to experimentally investigate the aforementioned effects on the ignition of RF arcs, with a particular focus on space charge effects and ion bombardment.

EXPERIMENT DESIGN

IBEX is based on the well-known concept of a quarter-wavelength resonator. The amplifier feeding point is connected to an open ended coaxial transmission line, and a matching network. Via tuning of the matching elements and operating frequency, resonance conditions in the transmission line are achieved (purely real impedance at the feeding point), and matching at the feeder with a 50 Ω impedance guarantees the maximum power coupling to the resonator.

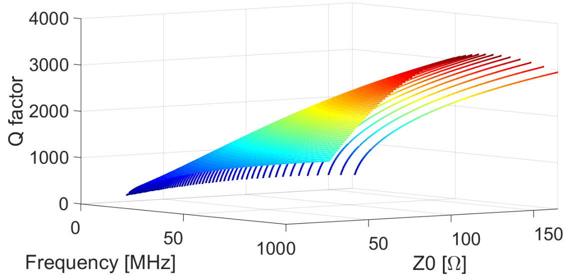


FIGURE 1: Q factor of stainless steel TL section

Due to limitations on power availability, a high Q-factor is necessary to achieve relevant voltages at the open-end electrode. The major design constraint is the maximum sustainable voltage at the vacuum feed-through, hence the length of the stainless steel part of the transmission line. Therefore, the main limitation on the Q-factor comes from the higher resistance section of the stainless steel TL. To keep a high Q-factor, an inner OFHC Cu conductor will be used. The characteristic impedance of the mixed-materials transmission line was optimized to achieve highest Q (Figure 1) at about 130 Ω.

The other requirement for IBEX is the compactness, in order to be able to interface easily with other experimental facilities. Hence the choice of the frequency (∼ 50 MHz) and a vacuum capacitor as tuning element, as opposed to a stub tuner, which would have caused uncertainties on the breakdown location (possible multipactor discharge) and the requirement of a rather bulky 3 m section of 9” TL to avoid arcing at the stub voltage maximum.

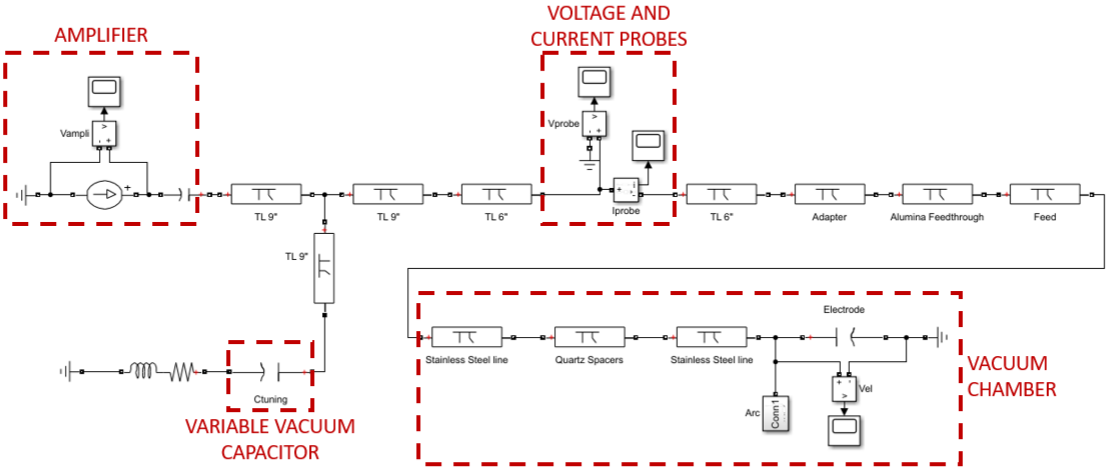


FIGURE 2: Circuit diagram of resonator

The physical components of the resonator have been characterized both in QucsStudio and MATLAB/Simulink, for cross-comparison of the system frequency response. Circuit schematic is represented in Figure 2.

Tuning of the resonator has been carried out with two techniques: minimization of the return loss on QucsStudio and state-variable analysis in MATLAB Simulink. In the latter method, Simulink produces the system matrices **A** of the circuit over a range of defined tuning capacitance values. MATLAB computes the eigenvalues of **A**, where the imaginary part represents the resonance frequency of the system.

Considering the amplifier as a voltage-controlled current source with a negative internal resistance, so that $i = Gv$ with $G < 0$, the system to solve is (1).

$$\begin{cases} \mathbf{x}' = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{s} \\ \mathbf{v} = \mathbf{C}\mathbf{x} \\ \mathbf{s} = \mathbf{i} = \mathbf{G}\mathbf{v} \end{cases} \tag{1}$$

A is the aforementioned system matrix, **C** is the output matrix, **x** is a vector containing capacitors and inductors voltages and **B** is the input matrix, **s** being the sources vector. In our case, having only one current source, **s** = **i**. G is iteratively modified for each working frequency, to minimize the real part of the eigenvalues (damping factor). This guarantees the maximum power transfer from the amplifier for each working frequency.

The capacitance at the open end of the resonator, defined by electrodes gap and their shape, is a sensitive parameter on the circuit resonance. Capacitance of various electrodes geometries was calculated with FEMM over a range of separation gaps, and included in the MATLAB Simulink model. Figure 3 shows optimal power coupling over a range of available tuning capacitor values, for 0.4 mm electrodes gap. The arc has been modelled in Simulink with a 20 nF inductance and a DC voltage source, representing the arc burning voltage.

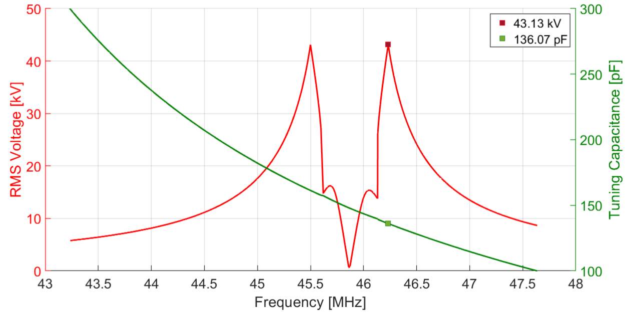
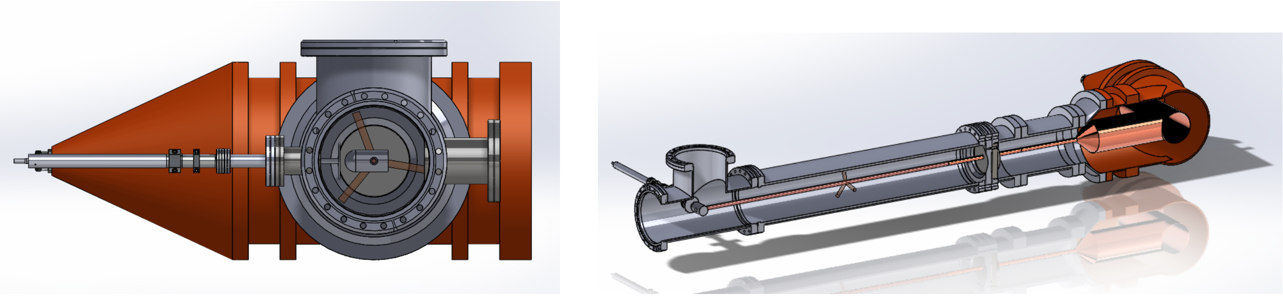


FIGURE 3: Optimized voltage at electrode

EXPERIMENTAL PLAN

The IBEX test stand is currently being assembled at IPP Garching (Fig. 4).

First experiments will be devoted to vacuum arcs at ICRF antenna relevant pressures ($10^{-4} \div 10^{-7}$ mbar), focusing on the measurement of field-emission current. The second phase will provide insights on the interaction of RF



(a)

(b)

FIGURE 4: IBEX: (a)Side view (b)Section view

structures with plasma, via the interface with IShTAR, a helicon source generating Argon plasmas up to densities of 10^{18} m^{-}3, and SIESTA, a hydrogen and deuterium ion source able to achieve fluxes of 10^{19}m^{-2}s^{-1}, with impinging energy up to 10 keV.

CONCLUSION

The power and reliability limits of ICRF systems are related to the maximum electric field achievable without breakdown. The electric field limit is currently a passively established value, experimentally defined by means of the operational space of various machines. This study aims at giving insights on the fundamental phenomena of arc ignition in the complex framework of RF structures in fusion-relevant environments. With a greater understanding of the underlying arc mechanisms, design criteria and targeted conditioning measures can be developed to increase the efficiency and attractiveness of ICRF in future reactors.

ACKNOWLEDGMENTS

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.

REFERENCES

[1] Durodié, F., et al. ”Performance assessment of the ITER ICRF antenna.” AIP Conference Proceedings. Vol. 1580. No. 1. AIP, 2014.

[2] Bobkov, V., et al. ”Influence of the plasma on ICRF antenna voltage limits.” Journal of nuclear materials 313 (2003): 956-961.

[3] Arredondo, R., et al. ”SIESTA: A high current ion source for erosion and retention studies.” Review of Scientific Instruments 89.10 (2018): 103501.

[4] Crombé, Kristel, et al. ”IShTAR: An international facility for studying the interactions between ICRF waves and plasma.” General Scientific Meeting of the Belgian Physical Society. 2016.

[5] Insepov, Z., Norem, J., Proslier, T., Huang, D., Mahalingam, S., Veitzer, S. (2010). Modeling rf breakdown arcs. arXiv preprint arXiv:1003.1736.

[6] Insepov, Z., Norem, J. (2013). Can surface cracks and unipolar arcs explain breakdown and gradient limits?. Journal of Vacuum Science and Technology A: Vacuum, Surfaces, and Films, 31(1), 011302.

[7] Lloyd, O., C. F. Gozna, and G. Jervis-Hunter. ”The initiation of arcs by ion bombardment.” Journal of Physics D: Applied Physics 3.11 (1970): 1670.

[8] Galdon-Quiroga, J., et al. ”Velocity space resolved absolute measurement of fast ion losses induced by a tearing mode in the ASDEX Upgrade tokamak.” Nuclear Fusion 58.3 (2018): 036005.