The Trapped Electron Experiment (T-REX): Commissioning and First Results

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Gyrotrons are the only sources used for electron cyclotron resonance heating (ECRH), and are considered as the primary ones for heating and current drive systems of fusion reactors, making their efficient operation crucial for the advancement of fusion energy. Past gyrotron experiments have highlighted some instability issues, leading to restricted operating ranges. One major cause is the presence of trapped electrons within the gyrotron's magnetron injection gun (MIG) region, resulting in undesired currents and subsequent operational failures. To avoid such issues, the current approach is mostly based on tight manufacturing tolerances for the MIG geometry [1]. We present initial experimental findings of the TRapped Electrons eXperiment (T-REX), a novel and unique plasma experiment constructed at the Swiss Plasma Center that aims to understand the underlying physics of formation and evolution of electron clouds in gyrotron MIG designs [2]. Their comprehensive understanding could serve to help relaxing some of the current gyrotron's tight manufacturing tolerances. The T-REX experiment replicates typical MIG geometries, electric and magnetic fields, and is supported by kinetic simulations via the 2D Particle-in-Cell (PIC) code FENNECS [3, 4]. The experimental set-up is characterized by two coaxial electrodes placed in a vacuum chamber mounted on top of a superconducting magnet. The central electrode is biased to negative DC voltages, while the outer one is at ground. This leads to an applied external radial electric field (1 to $100\,\mathrm{MV/m}$), and an axial magnetic field ($B < 0.4\,\mathrm{T}$) that induce azimuthal drifts and confining electron energies between 0.1 to $1\,\mathrm{keV}$. Such experimental setup bears resemblances to Penning traps. The geometry of the electrodes, electric and magnetic field configurations, as well as composition and pressure of the background gas, can be adjusted to replicate typical MIG parameters. We present experimental findings on the current distribution and electron cloud dimension based on imaging, for a set of applied voltages and magnetic fields, and compare those with simulation results performed with the FENNECS code. The planned diagnostics include also optical emission spectroscopy, a phosphor screen system, Streak camera imaging, and, potentially, electric field distribution via the Stark effect. Furthermore, T-REX is also designed to be capable of detecting potential growth of diocotron modes, via the aforementioned diagnostics in combination with a segmented outer electrode. Finally, we aim to gain valuable insights into the trapping and dynamics of electrons within MIG regions, paving the way for improved gyrotron performance and reliability in fusion energy systems.

I. INTRODUCTION

To achieve future fusion energy, both Tokamak and Stellarator configurations foresee using gyrotrons as the main electron cyclotron resonance heating (ECRH) devices [5]. ITER requires 24 gyrotrons [6–9], possibly up to 60 after recent wall material changes [10, 11]. DEMO requires 130 MW of power via gyrotrons [12]. Therefore, gyrotron efficient operation is crucial, and any design improvement to simplify construction and tolerances can reduce the manufacturing costs and times [13]. Gyrotron's main components are shown in Fig. 1.

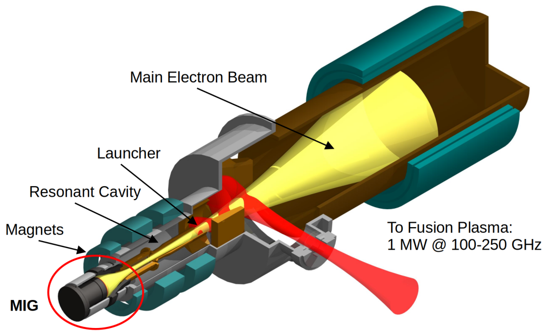

FIG. 1: Schematics of a Gyrotron and its Main Components [2, 14].

This article presents the development of a novel non-neutral plasma physics experiment, named TRapped Electrons eXperiment (T-REX), that aims to understand a specific issue, found in some gyrotron's magnetron injection gun (MIG), that arises due to trapped secondary electrons (not belonging to the main beam) that lead to limit nominal gyrotron operation and even causing unexpected gyrotron shutdowns [1]. Such secondary electrons are trapped in the MIG region in potential wells that form when magnetic field lines cross twice equipotential lines. The accumulation of electrons can cause large currents to arise inside the gyrotron, leading to damages and preventing to operate at nominal voltage bias. A deeper understanding of the physics behind those issues can lead to the discovery of new solutions for simplifying gyrotron manufacturing and construction. T-REX is designed and built at the Swiss Plasma Center of the EPFL and its primary objective is to explore the formation and evolution of electron clouds in MIG designs.

II. NON-NEUTRAL PLASMA AND ELECTRON TRAPPING

Electron clouds are non-neutral plasmas. Electron confinement can be achieved mainly in two ways: via magnetic mirror, or via a combination of electric and magnetic fields, see Fig. 2. Concerning the latter, which T-REX resembles, is the Penning-Malmberg trap [15–17]. A gyrotron's MIG, see Fig. 3, is similar as it provides a nearly axial magnetic field with coaxial electrodes biased at different voltages. In a MIG, the equipotential lines are shaped by the electrodes geometry, while the magnetic field, azimuthally symmetric and non-uniform, by the external magnets. The vacuum potential wells arise where magnetic field lines cross twice an equipotential line, see Fig. 2 [1]. Free electrons in the MIG region can be released from the background gas due to the large electric field applied or even from cosmic rays. The combination of the large crossed electric and magnetic fields leads to large $\vec{E} \times \vec{B}$ azimuthal drift, providing large kinetic energies to the electrons that ionize the neutrals. Ions are immediately lost while electrons are trapped in the potential well. As the number of electrons trapped increases, a path forms for undesired currents to flow via the electron cloud between the electrodes surfaces perturbing gyrotron's operation as well as damaging it. The current MIG design criteria includes shaping the electrodes according to the nominal magnetic field topology

FIG. 2: Electron Trapping via: Left: Magnetic Mirror, Right: Electric and Magnetic Fields [2, 4].