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Progress in Physics (41)

Electron Cyclotron Masers: from plasma physics to NMR spectroscopy applications

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1. Introduction

Gyrotrons belong to the family of high-power coherent radiation sources known as electron cyclotron masers (ECM) or cyclotron resonance masers (CRM). The physical mechanism in a CRM is based on the cyclotron maser instability (CMI) and is a result of the relativistic dependence of the electron cyclotron frequency on the electron energy [1]. This instability very efficiently converts rotational kinetic energy into coherent radiation even for weakly-relativistic conditions where the electron kinetic energy is small compared with its rest energy. Gyrotrons are fast-wave vacuum electronics devices, which are characterized by the fact that the wave-particle interaction is not localized near the walls of the interaction space (like in slow-wave devices characterized by a surface-wave interaction), but takes place in a large volume. This property enables the gyrotron to generate high-power coherent radiation in the sub-THz and THz frequency range at the MW level in continuous mode (CW). The worldwide R&D activity on gyrotrons [2] is mainly driven by the need for an intense source of coherent, millimeter-wave radiation to heat a magnetically confined fusion plasma [3,4] as will be the case in ITER [5] or the DEMO reactor which will follow ITER.

As a spin-off from the plasma physics related gyrotron R&D activity a novel application has been developed in the last two decades in the field of NMR spectroscopy, where a dramatic enhancement in sensitivity of the high-field NMR spectrometers has been achieved via Dynamic Nuclear Polarization (DNP) [6,7]. For a variety of applications based on this technique, a low power gyrotron (~1-10 W) radiating in the THz frequency domain is needed. Both research avenues for gyrotron applications, plasma physics and NMR spectroscopy, are pursued at the Centre de Recherches en Physique des Plasmas, EPFL, including experimental as well as theoretical/numerical studies. Guided by theoretical modeling, novel operational regimes characterized by nanosecond pulses have been recently experimentally demonstrated which may open new applications for gyrotrons.

2. Basics of Gyrotrons and CRM instability

In a gyrotron, a hollow electron beam is emitted and accelerated in a Magnetron Injection Gun (MIG), where an annular electron beam is created in a crossed electric and magnetic fields. The beam is guided by the magnetic field lines towards a resonant cavity with cylindrical symmetry. Between the MIG and the cavity, the electrons experience an increasing magnetic field, which amplifies their rotational kinetic energy via adiabatic compression. In the cavity, the wave-particle interaction takes place, which, in the most simple model, can be described by the dispersion relation of a magnetized weakly relativistic electron beam and the

dispersion relation of a transverse electric mode (TE) supported by the cavity. The intersection points of these two dispersion relations define the gyrotron operating points (see Figure 1). At the operating point and under some additional conditions, the CMI instability can take place and develops in different stages going from linear to strongly non-linear regimes. While the electrons traverse the cavity these stages can be distinguished as [1,2]: (a) energy modulation, (b) orbital bunching (relativistic effect), (see upper inset in Fig. 2) and (c) bunch deceleration. When the rf-wave frequency, defined by the resonant cavity, slightly exceeds the cyclotron frequency or its harmonics ($\omega > s \Omega_{ce}/\gamma$, s integer), a bunch is formed in the decelerating phase and electrons emit a coherent radiation. On the contrary, if $\omega < s \Omega_{ce}/\gamma$, a bunch is formed in the accelerating phase and the electrons absorb energy from the rf-wave. In the novel operational regime described below the accelerating and decelerating phases dynamically take place in the same interaction space and give rise to the nanosecond pulsed regime. Within the family of ECM, the specificity of the gyrotron relies on the fact that it operates close to cutoff ($k_{||} \approx 0$) which renders the CMI very insensitive to the electron beam velocity spread.

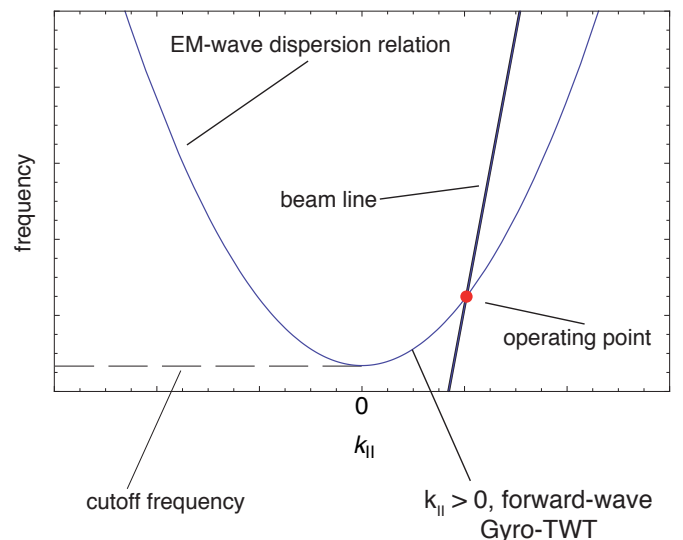


Fig. 1 Simplified uncoupled dispersion relation in the ω - $k_{||}$ space showing the electron beam dispersion relation (beam line) and the electromagnetic-wave dispersion relation (TE-mode supported by the cavity). The beam-line represents the Doppler shifted electron beam dispersion relation: $\omega = \Omega_{ce}/\gamma + k_{||}v_{||}$, with Ω_{ce} , γ , $k_{||}$, and $v_{||}$ the electron cyclotron angular frequency, the relativistic factor, the parallel wave-vector and parallel velocity respectively. The dispersion relation for a given TE transverse mode is given by $\omega = \omega_{co} (1 + c^2 k_{||}^2 / \omega_{co}^2)^{1/2}$, with ω_{co} and c being the cut-off angular frequency and the speed of light, respectively. The intersection point is the gyrotron operating point.

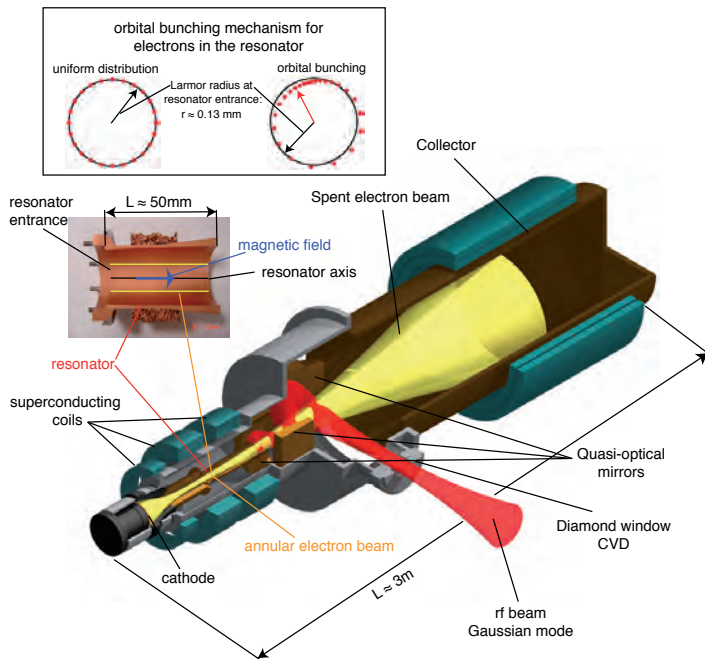


Fig. 2 Schematic of high-power high-frequency gyrotron for plasma heating applications. A hollow cross-section (annular) weakly-relativistic electron beam is guided by a strong magnetic field produced by a superconducting magnet and is injected into a resonant cavity. As the beam passes in the interaction region, defined by a cylindrical cavity supporting a TE mode, it experiences the CMI whereby electrons, initially uniformly distributed on a Larmor radius, undergo orbital bunching (see upper inset), causing them to be decelerated and emit coherent radiation. The lower inset is a photograph of the resonant cavity of a typical 1 MW-class gyrotron. The annular electron beam in the cavity has an average radius and thickness of 10 mm and 0.5 mm, respectively.

3. Applications from magnetically confined plasma heating to NMR spectroscopy

As described in [2], several decades of intensive R&D activity, on theory, experiment and industrial development, were needed to develop a state-of-the-art gyrotron meeting all the necessary requirements for the presently operated fusion devices [4] and in particular for ITER [8-10]. In Europe this effort is carried out by the EGYC¹ consortium in which CRPP is one of the main actors. The present dominant activity within EGYC, together with the industrial partner, the French company *Thales Electron Devices*, is devoted to the industrialization of the gyrotron for a series production in view of providing the electron cyclotron heating system of ITER with 6 CW-gyrotrons operating at 170 GHz and delivering 1 MW each [9]. In parallel to this activity EGYC is pursuing R&D aimed at significantly increasing the unit power as well as the frequency in view of the future demonstration power plant DEMO [10,11]. In Figure 2 is shown a schematic of a high-power, high-frequency gyrotron for fusion applications.

As a spin-off activity of the gyrotron R&D for plasma applications, the development of frequency-tunable gyrotrons in the THz frequency domain has been started in 2008 at EPFL in a joint effort with the Swiss-DNP-Initiative [12] (SDNPI). Within this joint effort, CRPP is responsible of developing the frequency-tunable gyrotron as well as the associated THz-instrumentation from the source (gyrotron)

¹ EGYC is a collaboration of CRPP, Switzerland; KIT, Germany; HELLAS, Greece; IFP-CNR, Italy.

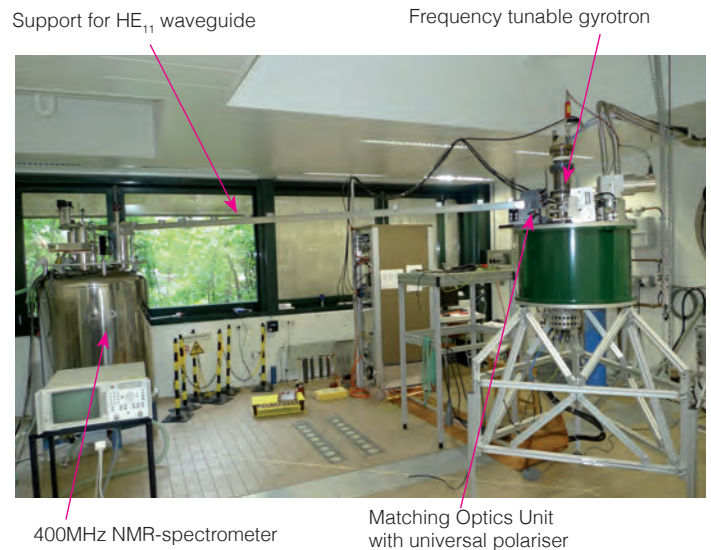


Fig. 3 Layout of the DNP-NMR experiment in the LPMN laboratory, with the gyrotron, the matching optics unit including a universal polarizer, the support of the corrugated waveguide propagating the HE_{11} mode and the variable field 400 MHz NMR spectrometer. The 4 m-long HE_{11} waveguide is manufactured by a spin-off company, Swissto12, using a stacked ring technique [14].

to the sample under investigation [13]. Figure 3 shows the present layout for DNP-NMR experiments to be carried out at the Laboratoire de Physique des Matériaux Nanostructurés (LPMN) of EPFL.

Within this activity, the company Swissto12 has been created and is a spin-off of CRPP with strong support of Laboratoire de Physique des Matériaux Nanostructurés (LPMN) of EPFL.

4. From linear to non-linear up to chaotic ECM regimes: theory and experiment

The development of new theoretical models not only benefits the effort in the domain of R&D of gyrotron for fusion applications, as well as the development of advanced gyrotron concepts for DNP in the field of NMR spectroscopy, but also allows to gain a deeper understanding of the underlying complex non-linear wave-particle dynamics occurring in a CRM. Based on a non-linear interaction code developed at CRPP, novel dynamical regimes have been predicted for the gyrotron designed for DNP/NMR applications and have been confirmed experimentally [15,16].

The novel operational regimes predicted by the TWANG code have been experimentally confirmed with the gyrotron developed for DNP/NMR applications. This gyrotron has demonstrated to be an ideal test-bench for fundamental research on the complex non-linear dynamics in ECMs. For the first time it has been possible to experimentally investigate the dynamical properties from the linear regime up to chaotic regimes reached via a “period doubling cascade” [15]. Among a wide variety of non-stationary regimes, a nanosecond pulsed regime has been discovered and is interpreted as the consequence of a self-consistent Q-switch effect in which the self-consistent diffraction quality factor is dynamically modulated by driving the gyrotron in a strongly nonlinear regime with phase-locked sidebands

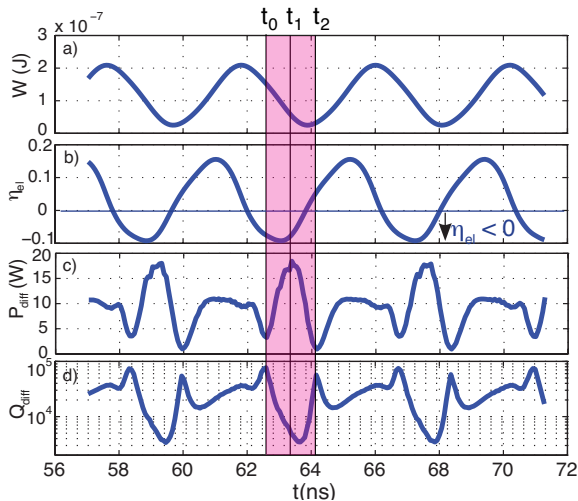


Fig. 4 Time traces obtained with the TWANG simulation code: a) cavity stored energy, b) interaction efficiency, c) radiation power, d) self-consistent diffraction quality factor. The red rectangle highlights a single nanosecond pulse.

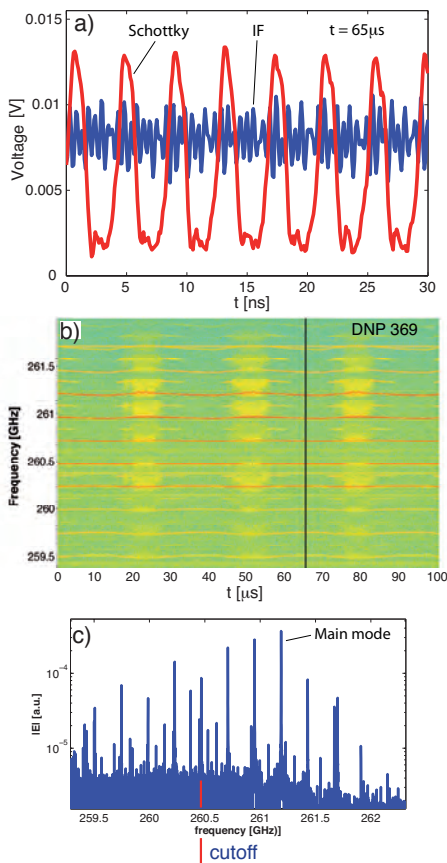


Fig. 5 Experimental results corresponding to the simulations of Fig. 4 are shown in a) in red, instantaneous RF-power measured with a wide bandwidth (DC-20GHz) Schottky diode. In blue intermediate frequency signal from a heterodyne receiver. b) spectrogram with 100ns resolution calculated from IF-signal of heterodyne receiver. c) radiation field spectrum (FFT) taken at time = 65 μ s of the 100 μ s long acquired signal. The frequency-equidistant side-bands are clearly visible in subplots b) and c). The cut-off frequency in the constant cavity radius is indicated in subplot c) by the red line.

[16]. The relevant time traces comparing theory and experiment are shown in Fig. 4 for the simulations and Fig. 5 for the experiment.

Further experimental studies as well as theoretical development will be aimed on the control of the pulse length, duty cycle and modulation depth within the nanosecond pulsed regime.

Going from the first proof-of principle of CRM's to the present recent achievements has required substantial progress in experiments, theoretical/numerical modeling

and technology. The strong interplay between theory and experiment has been and still will be essential for gaining deeper understanding of the complex underlying non-linear physics of CRM's.

Acknowledgments

For plasma physics related applications this work is partially supported by EFDA under Grant WP13-DAS-HCD-EC and by Fusion for Energy under Grant F4E-GRT-432 within the European Gyrotron Consortium (EGYC). For DNP/NMR applications this work is partially supported by Requip (206021-121303/1 and 206021_144983), Sinergia (CRSI20-122708/1), and (200020-120503/1) grants of the Swiss National Science Foundation, by the School of Basic Science of EPFL and by the EPFL.

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