Status of ENEA 250 GHz Cyclotron Autoresonance Maser Project

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Abstract—**The conceptual design study of a high-power high-frequency Cyclotron Auto-Resonance Maser (CARM) has been undertaken at the ENEA-Frascati research center in 2013. CARMs could be effective mm-wave sources for electron cyclotron waves and plasma diagnostics in magnetic confinement fusion reactors. The project is advancing quickly with the technical design of some major parts now completed and ready to enter the realization phase. Subsystems under conceptual or detailed design are presented together with the outlook of next steps.**

I. INTRODUCTION

CYCLOTRON auto-resonance masers (CARMs) [1] attracted much attention in the 1990s, but the initial expectations were not fully met due, first of all, to the low quality of available electron beams. Nowadays many problems, which prevented the successful generation of medium-order modes in a highly oversized Bragg cavity, have been overcome, paving the way to the project of a 250 GHz CARM device at ENEA [2]. The first phase of this activity aims at demonstrating the feasibility of a 200 kW CARM-type vacuum tube for pulses up to 0.2 s, while the long-term goal is the realization of a 1 MW, CW vacuum electron device.

The CARM has interesting features that make it an attractive mm-wave source for plasma heating and diagnostics in fusion reactors like DEMO [3]. Indeed, by exploiting moderately relativistic electron beams and the Doppler upshifted cyclotron wave, CARMs can operate with a mode far from its cut-off frequency, allowing a significant reduction of the static magnetic field in the interaction region, i.e. the cavity. Furthermore the use of lower-order modes with respect to non-coaxial gyrotrons can give beneficial effects on mode competition and ohmic losses. Differently from gyrotrons, the energy of both axial motion and gyration is withdrawn from electrons and converted into microwave radiation energy. Besides, due to the autoresonance condition, the synchronism between particles and wave is hold during the entire interaction path.

The ENEA project has made significant progress during last year. The technical design of the High Voltage Power Supply (HVPS) has been completed, while the electron gun is ready to enter the final mechanical analyses and blueprint phase. The conceptual design of the cavity is close to completion and the components for the cold-test are in an advanced design phase. Nevertheless, much work has still to be carried out, particularly as regards solenoids, gun emitter ring and vacuum system, just to cite a few.

II. PROGRESS WITH THE ENEA CARM

The most challenging requirement of the HVPS is the combination of the very high voltage of 500÷700 kV, close to the power supply of ITER neutral beam injectors, with the needs of high stability and precision. The CARM modulator has to achieve a pulse to pulse, as well as within a pulse, voltage variation < 0.1% together with an overshoot < 2%. A multi-primary pulse transformer is expected to meet the requirements under the control of the Pulse Width Modulation (PWM) technology. The pulse transformer will be hosted in an oil-filled tank, where the electron gun is plugged. The maximum energy delivered in case of a CARM inner electric breakdown is limited to 10 Joules.

The electron gun is a diode-type thermionic electron gun operating at full power in temperature-limited regime. The shape of cathode and anode has been designed with a minimum vacuum distance of 110 mm and limiting the surface electric field to 8 kV/mm, a value that is localized around the emitting ring. The latter has a width of 1 mm and operates at about 1300 °C. Emitted electrons follow helical paths and are arranged in a hollow electron beam.

An electric field kick, close to the input of the drift tube, determines the required relativistic factor γ around 2-2.5, together with a pitch ratio α, predicted with a commercial code (CST Studio Suite), lower than 0.5. A critical parameter for CARM efficiency is the longitudinal velocity spread. By operating the gun at high voltage and low current, a predicted value of 0.005 has been achieved in the simulations, providing confidence on the high quality of the generated electron beam. The latter moves from the electron gun to the cavity with maximum static magnetic fields of 0.5 T and 7 T, respectively. The main magnet is realized with a superconductive coil, which is currently under design.

A numerical tool has been developed for a quick, approximate evaluation of the electron motion along the tube. The code is primarily conceived for a flexible, preliminary calculation of the annular shape of the electron beam so as to envisage possible improvement to the width. Fig. 1 shows the spots of the electron beam in the transversal plane at the emitter and inside the cavity. Recently some effort has been put in implementing a variable mesh in longitudinal direction to cope with high magnetic field gradient at the input of the cavity.

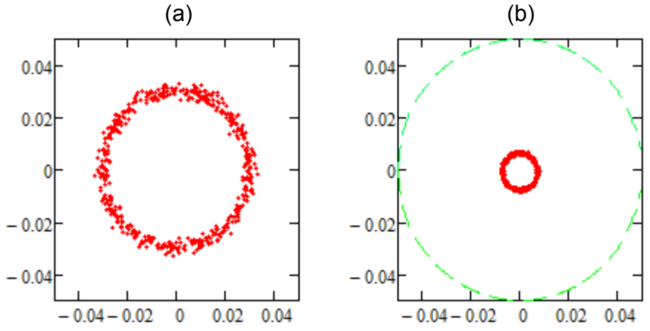

Fig. 1. Electron beam in the transversal plane [mm] at the emitter (a) and in the middle of the high-field region (b); the position of the solenoid (dashed curve) is also shown.

The cavity is a circular waveguide with diameter of 15 mm, enclosed between two Bragg-type conventional reflectors. A one-to-one correspondence between CARM and FEL (Free Electron Laser) equations was derived to relate the main parameters of the device [4]. According to this analytical tool, the most suitable solution in terms of efficiency and allowable power density was found with a cavity resonating at 258.1 GHz, working with the $TE_{8,2}$ mode and exhibiting a Q-factor of around $3.5x10^3$.

A resonator, which meets previous requirements, has been designed with an in-house code that implements the coupled-mode theory, i.e., an approximate, semi-analytical, modal method for the study of waveguides with slowly varying cross-section. The quality factor of Fig. 2 has been obtained with a structure made of copper and consisting of a 180.59 mm long central cavity and two rippled-wall waveguides with 700 (upstream) and 120 (downstream) sinusoidal corrugations, respectively. Such a design corresponds to a very long device and its fabrication exhibits serious technological challenges, for which the suitability of advanced micromachining techniques is currently under assessment. To get a preliminary picture of mode competition, the numerical tool based on the couple-mode equations has been applied to all modes, the dispersion curve of which intersects the beam line in the Brillouin diagram. The propagating modes with intersection very close to their cutoff frequency, exhibit even higher quality factors than the operational mode, but they are mostly dissipated owing to ohmic attenuation.

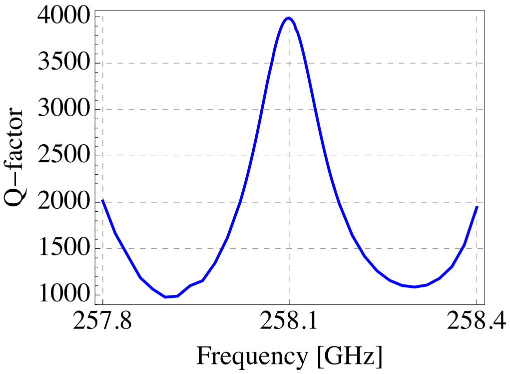

Fig. 1. Q-factor of the Bragg cavity of the ENEA CARM.

For a meticulous calculation of power losses quality factor, a full-wave code is preferred. Approximate formulas give different results, while the coupled-mode theory is sensitive to the side the resonator is fed from and its formulation does not easily allow the internal excitation of the cavity. The solvers of commercial softwares cannot address very long devices, so a code based on the mode-matching method has been specifically developed for Bragg reflectors and its application to the full resonator and Q-factor calculation is ongoing.

Recently much effort has been devoted to the conceptual design of an experimental cold characterization for the cavity. Fabrication issues may shift the resonant frequency, so the mode conversion chain should ideally provide a pure $TE_{8,2}$ mode over a large bandwidth (around 4%) at the input of the resonator. No solution able to meet the bandwidth requirement has been found so far. Two configurations were assessed to a larger extent and a third alternative is under investigation. The former were designed with CST Microwave Studio and their most critical converters are shown in Fig. 3. The one employs a longitudinal and azimuthal periodic perturbation of the waveguide wall to achieve beat-wave coupling between the $TE_{1,1}$ and the $TE_{8,1}$ mode; the other relies on a slotted wall, where properly phased incoming waves excite the $TE_{8,1}$. The second configuration has better performances and a simpler geometry [5]. Further transitions and converters are less challenging under both design and fabrication viewpoint.

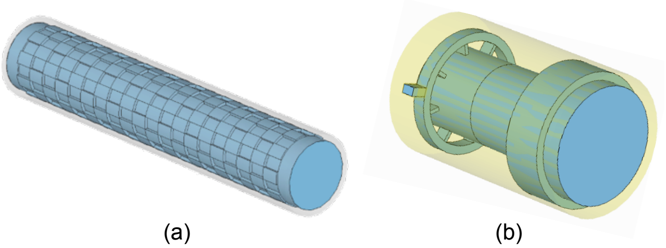

Fig. 3. Beat-wave (a) and side-coupling (b) mode converters.

III. SUMMARY

The ENEA CARM project is advancing and interesting contacts have been established with international institutions such as the Institute of Applied Physics (Russian Academy of Sciences). A more accurate modeling of the beam-wave interaction region is under development together with the progresses of the engineering design.

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