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Comparison of reflector concepts for a 250 GHz CARM cavity

S. Ceccuzzi, G. Dattoli, E. Di Palma, A. Doria, G.P. Gallerano, G.L. Ravera, I. Spassovsky, A.A. Tuccillo, ENEA CARM Team*

ENEA Fusion Department, Frascati, Italy, silvio.ceccuzzi@enea.it

Introduction

The state-of-the-art on efficient high-power continuous-wave (CW) sources of coherent mm-wave radiation cannot meet the challenging future demands that mostly come from diagnostic as well as heating and current drive systems in thermonuclear fusion research. Intensive R&D is required to attain a cost-effective vacuum tube suitable to work with reactor-relevant tokamaks, even pushing forward with gyrotron technology, which is the most mature nowadays [1]. In parallel with gyrotron development, it can be thus useful to consider other source concepts like the Cyclotron Auto-Resonance Maser (CARM), theoretically promising for mm waves [2].

The study of a 250 GHz CARM for nuclear fusion was undertaken [3], aiming at a CW power of 1 MW to be pursued through intermediate steps of lower power and shorter pulse length. Some advantages of this source compared to gyrotrons are lower static magnetic field in the interaction cavity and lower ohmic losses per unit length. Such strengths are subordinate to the fulfillment of severe requirements, e.g., in terms of quality of the electron beam, stability of the high voltage modulator, and mechanical precision of the resonant cavity. Concerning the latter, the upstream mirror represents the most critical element from the realization viewpoint due to its around 800 ripples if based on the traditional Bragg reflector.

To identify the most convenient design, different types of mirror have been assessed. With respect to a recent comparison between traditional and advanced Bragg designs [4], reflectors based on tapered mean radius, trapped mode and discrete mirror are also considered here.

Comparison of reflectors

The reflector input is a circular waveguide with diameter larger than or equal to 15 mm to keep the power density for the operational TE_{53} mode below the safety threshold. Different mirror concepts have been designed maximizing the reflectivity at 250 GHz for the TE_{53} mode and constraining the transmitted power (i.e., the one flowing toward the gun) to be lower than 0.5%. For reflectors based on rippled-wall waveguides, step-type ripples have been considered. Moreover the depth of the first ripples at each side of the mirror has been tapered to reduce the level of side lobes. In the presence of multiple designs with similar performance for the same reflector type, shorter geometries have been preferred.

The types of mirror considered for this study are depicted in Fig. 1. The first one (Fig. 1a) is the traditional distributed reflector [5], based on the coupling between the forward and backward waves of the same mode. This coupling takes place by providing the waveguide wall with a small periodic perturbation that satisfies the Bragg condition, i.e., with period equal to $\lambda_g/2$, being λ_g the mode wavelength in the unperturbed waveguide. The second type of mirror (Fig. 1b) is the advanced Bragg reflector [6], i.e., a rippled-wall waveguide with the perturbation period equal to λ_g. Such condition leads to a three-wave coupling between the partial waves of the operational mode and a quasi-cutoff mode that is the $TE_{5,11}$ if the waveguide diameter is increased to 15.17 mm. The third option (Fig. 1c) is a traditional mirror having a section with tapered mean radius on the gun side. This configuration is mostly interesting because it allows a larger flexibility in tapering the radius of the annular electron beam that will pass through the resonator. The forth type of mirror (Fig. 1d) is the trapped-mode reflector [7], comprised of a taper and a backward mode converter. The TE_{53} moves to a rippled-wall section with a larger diameter of 17 mm, where it is counter coupled to the $TE_{5,12}$, being the period of the corrugations equal to $(1/\lambda_{TE5,3} + 1/\lambda_{TE5,12})^{-1}$. This high-order mode propagates back and, when passing through the down-taper, it is totally reflected because it becomes evanescent. A return trip takes place across the rippled-wall section with the $TE_{5,12}$ losing its energy in favor of the backward propagating TE_{53} mode. The last configuration (Fig. 1e) is a discrete mirror, made up of a step variation of the waveguide diameter after an adiabatic transition to a larger cross-section. If the waveguide cross-section is expanded sufficiently, its abrupt reduction can entirely intercept the non-zero transversal pattern of the operational mode and reflect it.

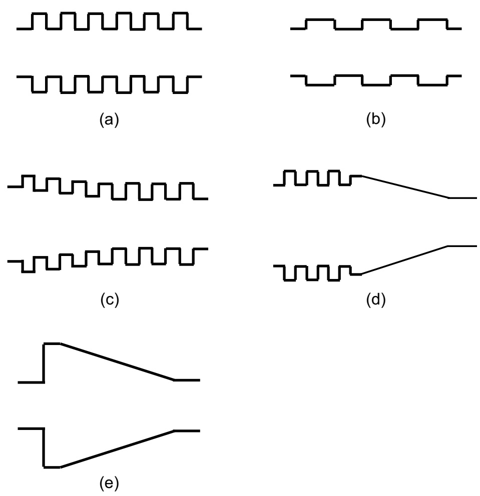

Fig. 1. Mirrors: (a) traditional Bragg, (b) advanced Bragg, (c) like (a) + rippled-wall section with tapered mean radius, (d) trapped mode reflector, (e) discrete reflector + taper

* See *Artioli M. et al.* Conceptual design report. A 250 GHz radio frequency CARM source for plasma fusion, edited by ENEA. 2016. ISBN: 978-88-8286-339-5.

An effective mode-matching code has been specifically developed to optimize the design of these oversized structures and provide a computation of losses according to perturbation method and attenuation constants. The reflectivity of the TE_{53} mode for each optimized mirror is shown in Fig. 2. These performances have been obtained with reflector lengths of around 0.51 m, 0.25 m, 0.7 m, 0.77 m and 0.6 m for the configurations of Fig. 1 from (a) to (e).

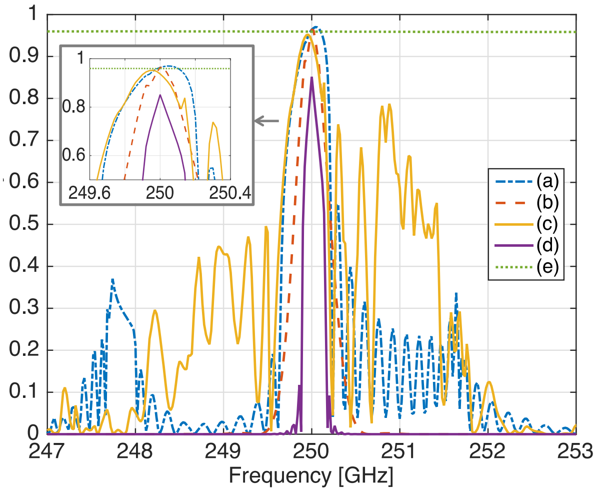

Fig. 2. Reflectivity of the optimized reflectors of Fig. 1

The discrete mirror has no variation in the plotted frequency range and its selectivity with respect to non-working modes is also extremely poor. For a taper length of 600 mm, acceptable reflectivity is obtained narrowing the waveguide down to a diameter not larger than 10 mm. This is a rather low value that conflicts with the transport of the electron beam and complicates the associated magnet system. The requirements of the latter can be relaxed using the Bragg reflector with up-tapered mean diameter. Apart from the very large side wiggles of this solution, the major drawback is the need of a longer device because the coupling between forward and reflected waves becomes less effective as the waveguide radius increases. Side wiggles can be eliminated choosing the trapped mode reflector, whose main advantage consists in a reflectivity lobe that is very steep. Nevertheless this solution is accompanied with high ohmic losses because it relies on a mode that becomes evanescent in the tapered section. Losses of the order of 14% have been computed for a rippled-wall section with a diameter of 17 mm; a larger cross-section would lead to a slightly lower dissipation and a longer device. The most attractive concept looks the advanced Bragg mirror that achieves a reflectivity of around 96.5% with the shortest length. Nevertheless its performance is very sensitive to a deviation of the geometrical dimensions from the nominal design values. In particular a variation of ±1 μm in the ripple period only produces a shift of a few hundreds of MHz in the reflectivity curves of other rippled-wall reflectors, whereas in the advanced mirror it noticeably impairs the frequency response of the structure. Finally the traditional Bragg mirror achieves a good compromise between selectivity performance, total length, ohmic dissipation and resilience to manufacturing errors.

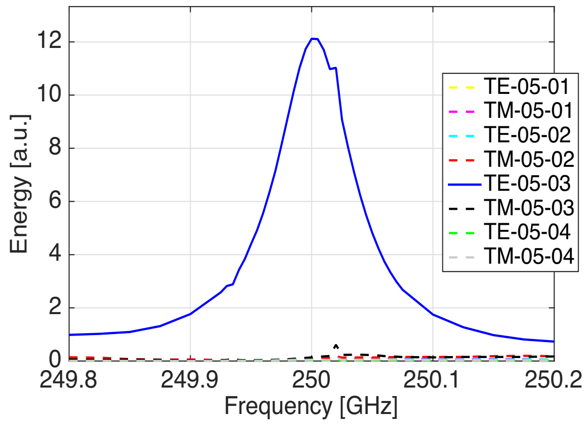

Fig. 3. Behaviour of a resonator with Q ≈ 3000

A resonant cavity has been thus designed relying on the traditional Bragg concept. The downstream mirror has been designed to achieve a quality factor of around 3000, considering a smooth-wall section of 10 cm. The final resonator, whose predicted behaviour is shown in Fig. 3, has a total length of 0.63 m.

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