Quasi-optical converters for high-power gyrotrons: a brief review of physical models, numerical methods and computer codes

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Abstract. Quasi-optical (QO) mode converters are used to transform electromagnetic waves of complex structure and polarization generated in gyrotron cavities into a linearly polarized, Gaussian-like beam suitable for transmission. The efficiency of this conversion as well as the maintenance of low level of diffraction losses are crucial for the implementation of powerful gyrotrons as radiation sources for electron-cyclotron-resonance heating of fusion plasmas. The use of adequate physical models, efficient numerical schemes and up-to-date computer codes may provide the high accuracy necessary for the design and analysis of these devices. In this review, we briefly sketch the most commonly used QO converters, the mathematical base they have been treated on and the basic features of the numerical schemes used. Further on, we discuss the applicability of several commercially available and free software packages, their advantages and drawbacks, for solving QO related problems.

1. Introduction

Gyrotrons represent a subclass of the electron cyclotron maser (ECM) devices, being close relatives to such sources of coherent radiation as free electron lasers (FEL) and conventional laser systems, but grounded on different physical phenomena [1–3]. Their operation is based on the so called electron cyclotron instability, where an electromagnetic (EM) wave stimulates formation of azimuthal and axial bunches in a flow of electrons that propagate in a constant homogeneous magnetic field and gyrate with the electron cyclotron frequency; on their turn the bunches enhance the wave by coherent bremsstrahlung. The physical nature of the gyrotrons could be briefly summarized by mentioning that (i) the gyrotron operation is based on relativistic effects – the dependence of electron cyclotron...
frequency on electron velocity via the electron mass, which is essential for the azimuthal electron beam bunching; (ii) while an excited atom emits exactly one photon per elementary act of wave–particle interaction, one electron can emit many \((10^3 - 10^8)\) photons with energy much less than that of the electron itself; in that sense gyrotrons, unlike lasers, are classical systems; (iii) as the generated EM wave phase velocity is greater than the speed of light, the gyrotron is a fast wave device, contrary to the conventional microwave devices as traveling wave tubes (TWT), klystrons and other slow wave devices. The practical importance of gyrotrons and their realized or potential applications is hard to overestimate. Gyrotrons fill the sub-millimeter gap between the infrared lasers and the conventional microwave tubes, providing EM beams of high average output power (1 MW and more) and long duration of operation (continuous-wave regime of several seconds to several minutes and more). Among the numerous applications in various fields one should mention fusion plasma heating and diagnostics, accelerator physics, material processing, radars and communications.

This paper is devoted to an indispensable part of the high-power gyrotron, namely, the quasi-optical (QO) mode converter. It is organized as a brief review of the basic types of mode converters (section 2), some considerations on the physical and mathematical aspects of their modelling (section 3) and a concise survey on some software packages for numerical electromagnetic computation and simulation (section 4).

2. Quasi-optical converters – basic schemes, their development and optimization

The progress in the development of powerful gyrotrons has been achieved by systematic and careful optimization of their parts (magnet, high-voltage supply, electron gun, depressed collector, resonator, quasi-optical converter, RF window etc., see figure 1). One of the most challenging problems appears to be the efficient outlet of the generated high-power EM radiation outside the tube. In the usual regime of operation high-order bulk modes are excited in the gyrotron cavity. They are characterized by high azimuthal and radial indices, circular polarization and radiation pattern in the form of a hollow cone. Such radiation is inconvenient for direct use and is difficult to transmit either, mainly because of the high loss level in the transmission lines. The QO mode converter placed between the cavity and the output window is intended to convert the gyrotron cavity modes into a linearly polarized Gaussian beam (figure 2). That beam is appropriate to be used directly as a free space TEM\(_{00}\) mode, or to be transmitted as a low-loss hybrid HE\(_{11}\) mode in highly overmoded corrugated waveguides. The efficiency of this conversion is crucial for high-power gyrotrons, bearing in mind that minimizing conversion and diffraction losses means not simply increasing output power, but far more solving severe cooling problems and avoiding device destruction.

Further on, without entering into details (the reader could find them in the review paper [4]), we briefly report on some general features of QO mode converters. The conventional waveguide mode converters used outside earlier gyrotrons are in the form of rippled-wall or corrugated circular waveguides and serpentine structures. These are devices of high efficiency but large size and narrow bandwidth and thus are not appropriate for implementation in high-power gyrotrons. There are mainly two types of quasi-optical converters that are used instead, namely the Vlasov converter [5] and its modification, the Denisov converter [6, 7]. The Vlasov converter represents a smooth surface circular waveguide, with a cut (stepped, slant or helical one, as shown on figure 2) acting as a launcher, combined with a parabolic reflector that forms the Gaussian wave beam. Two-reflector devices (with elliptic and parabolic mirrors) that focus the EM beam in two perpendicular planes onto a spot, e.g. for diagnostics purposes in a tokamak plasma, have also been reported [8]. In general, Vlasov converters are of moderate efficiency (typically 80%), require large mirrors for higher order modes and are somewhat impractical to be embedded in gyrotrons. The Denisov converter consists of a pre-bunching section (instead of the smooth surface circular waveguide in Vlasov converters) with a helical-cut aperture (figure 3) and up to 4 reflectors (cylindrical, quasi-parabolic and phase correcting ones [9, 10]). The pre-bunching (or field pre-shaping) section represents a rippled-wall (dimpled) waveguide of relatively short length; its role is to transform the gyrotron cavity mode into a bundle of modes that form a Gaussian intensity profile at the aperture, prior to the reflectors (in Vlasov converters such...
profile is formed after the uniformly profiled beam is reflected from the parabolic mirror). Denisov converters have higher conversion efficiency (about 95% and more) and smaller mirror size that makes them suitable to built-in in gyrotrons. A new, improved launcher, having two sections (a dimpled and a smooth one) has been proposed [11, 12]. The first section creates the bundle of modes with appropriate amplitudes, while the other one provides the necessary phase shifts between the modes. Tapered average section radius has also been considered in order to suppress spurious oscillations generated by the spent electron beam [11–13].

The numerical analysis, the modelling and design of QO mode converters [13–18] go together with their experimental approval (cold and hot measurements, corresponding to low- and high-power tests, respectively), following the main goals, namely to increase the conversion efficiency, to achieve an acceptable (less than 5%) level of diffraction losses and to reduce side-lobes to a minimum, keeping a reasonable device length. These goals have been reached by introducing different sections [11, 12], by optimizing the wall perturbations (dimples) of the converter pre-bunching section [13] and by adjusting and shaping (figure 4) the converter reflectors [3, 19–21]. Since the converters’ size tends to decrease and their geometry becomes more and more complicated, the QO converter modelling and

Figure 1. Schematic layout of a high-power gyrotron with an internal QO mode converter [2]

Figure 2. Vlasov converter. Examples [8] and an illustration of TE$_{15,4}$ mode to Gaussian beam conversion [3]
optimization requires careful choice of physical models as well as fast, accurate and stable numerical schemes.

**Figure 3.** Dimpled waveguide section [2]

**Figure 4.** Mirror shaping for high-power gyrotron QO converters [3]

**Figure 5.** QO launcher radiation pattern before and after optimization by using **SURF3D** [33]

### 3. Some physical and mathematical aspects of quasi-optical converter modelling

The physical and mathematical base of QO mode converter modelling somewhat reflects their two-part structure. *The coupled mode theory in irregular waveguides* [22] has been used to analyze the operation of the pre-bunching waveguide and to optimize its shape in order to achieve full (100%) conversion of the gyrotron cavity mode into a bundle of modes with a Gaussian-like intensity profile at a minimum waveguide length. The problem is reduced to solving a set of $N$ first-order linear ordinary differential equations for the amplitudes of the $N$ waveguide modes, with coefficients obtained by a small perturbation analysis of the structure. On the other side, *the Stratton–Chu vector diffraction theory* [23] has been used to simulate the radiation at the waveguide aperture and predict the properties of the launched EM beam at different positions along the propagation distance, in order to modify and improve the mirrors’ design. The problem which appears is that a size of several tens of wavelengths (the typical diameter of the QO converters is about 20 wavelengths) is far beyond the validity of the Geometric Optics (GO)/Geometric Theory of Diffraction (GTD) – it requires distances much greater than $10^3$ wavelengths. But at the same time GO/GTD is too much for a numerical procedure based on the Physical Optics (PO)/Physical Theory of Diffraction (PTD) to be effective. However, a new technique based on the method of equivalent edge currents was used to estimate backscattering effects due to diffraction at the cuts of Vlasov launchers [17].

It has been stated [24], that the combination of the coupled mode analysis with the Stratton–Chu diffraction theory cannot assure the necessary accuracy to achieve more than 90% efficiency of the designed QO converters. Another method has been proposed instead – *the surface field integral equation analysis*. It combines a well known, but for many reasons not widely used method for treatment of QO-related problems, integral formulation of Maxwell’s equations with advanced numerical techniques for solving integral equations for large body EM scattering, that significantly reduce computation requirements. There are several kinds of such integral formulations: Electric Field Integral Equation (EFIE) – well suited for thin wire structures of small to vanishing conductor volume and objects with opened conducting surfaces, Magnetic Field Integral Equation (MFIE) – appropriate for non-vanishing conductor volume structures with large smooth closed surfaces and EFIE/MFIE – used in the case of a combination of wires and smooth surfaces.

The traditional numerical method of solving EFIE, MFIE and EFIE/MFIE is the method of moments. It has been suggested almost a century ago and later on widely implemented in electromagnetic computations by Poggio and Miller [25, 26]. Consider the general linear operator equation

$$L f = e,$$

(1)
where \( e \) is the known excitation and the unknown response \( f \) is represented as a linear superposition of appropriate set of basis functions \( \{ f_j \} \):

\[
f = \sum_j a_j f_j .
\]

By using appropriate weighting functions \( \{ w_j \} \) one may compute \( G_{ij} = \langle w_i, L f_j \rangle \) and \( E_i = \langle w_i, e \rangle \), where the inner product for a linear surface integral operator equation is defined as

\[
\langle f, g \rangle = \iint f(\vec{r}) g(\vec{r}) \, d\vec{S},
\]

and the integration is performed over the conducting surface. Hence the linear integral operator equation (1) may be represented in matrix form \( G A = E \) with a solution \( A = G^{-1} E \), where \( G = \{ G_{ij} \} \), \( A = \{ a_j \} \) and \( E = \{ E_i \} \). Various choices of weighting functions are possible; the simplest one, \( w_j(\vec{r}) = \delta(\vec{r} - \vec{r}_j) \), is used in the NEC software package, while \( w_j(\vec{r}) = f_j(\vec{r}) \) reproduces the well-known Galerkin’s method. Thus the task of numerically solving the integral equation is transformed into finding a solution to a (huge) set of simultaneous linear equations, tractable by numerous effective solution and optimization schemes, e.g. by Gauss–Jordan inversion or by a factorization of the linear system and subsequent forward/backward substitution.

4. Software packages for electromagnetic computation and simulation

We restrict ourselves with listing some basic features of several most widely used software packages for solving three-dimensional (3D) EM problems, leaving aside 2D and 2.5D EM codes as Sonnet, partial differential equation (PDE) solvers like Poisson Superfish (the old Los Alamos National Lab PDE solver) and POOMA (a collection of parallel PDE solver tools), and physical optics packages as the Diffacted Element CAD (DECAD). We have chosen the Numerical Electromagnetics Code (NEC), the products of the Computer Simulation Technology (CST) – Microwave Studio (MWS) and MAFIA4, the High-Frequency Structure Simulator (HFSS), as well as the software development program products of Calabazas Creek Research, Inc. – Cascade and SURF3D, as a basic set of codes that represents the state-of-the-art in the field of EM computation and simulation.

4.1. Numerical Electromagnetics Code (NEC)

The Numerical Electromagnetic Code (NEC) represents the history of the EM code packages and, remarkably, is still in use [27–30]. It is a successor of an antenna modelling program (AMP) dated 1970; NEC2 (created in 1981) is the highest public domain package and NEC4 (appeared in 1992) is the highest licensed version (of Lawrence Livermore National Labs). It is based on the Method-Of-Moments techniques to numerically solve electric, magnetic or hybrid field integral equations for the currents induced by sources or incident fields. The structures in NEC are described by using elementary objects as wires and surface patches (triangle, rectangular or quadrilateral). Edges are not explicitly treated but could be represented as sets of smaller surface patches. The size requirements are as follows: (i) wires – 0.001 <segment length/wavelength < 0.1; (ii) surface patches – minimum 25 patches per square wavelength. NEC has no internal limits except those imposed by the hardware (available memory, speed) and the operational system (addressable memory and internal representations). However, the computational complexity for a structure of \( N \) segments increases with \( N^3 \) and the use of NEC becomes impractical for large \( N \), where the standard analytical approximations of GO, GTD, PO and PTD are considered as more appropriate. The method of moments was used in [17] for analysis of QO launchers.
4.2. Computer Simulation Technology (CST) products – MWS and MAFIA4

The Microwave Studio (MWS) [31] is a 3D EM field simulation package, based on the Finite Integration Method (FIM) – a consistent formulation of Maxwell’s equations on numerical grids that conserves electric charge and EM energy and ensures stability and convergence. As an advantage over the other CST product – MAFIA4, it uses also the Perfect Boundary Approximation (PBA) technique that provides conformal description of arbitrary geometry on a Cartesian grid, the Thin Sheet Technique (TST™) that assures independent treatment of two dielectric parts separated by a metallic sheet in a cell, and the Multilevel Subgridding Scheme (MSS™) that allows mesh lines to start and end anywhere in the simulation area. MWS is a configurable tool consisting of All Solver Block and one to four solver modules – Transient Solver, Eigenmode Solver, Frequency Domain Solver and Model Order Reduction Solver. In addition, it has 64-bit computing for some modules, optional multiprocessor support (parallel computing version for two processors on one mainboard), data exchange with Excel, Powerpoint and Matlab, a link to MAFIA4 and possibility for integration in a larger design environment as the CST DESIGN STUDIO.

MAFIA4 [31] is an advanced, versatile and sophisticated multi-purpose electronic CAD system, intended to solve EM problems ranging from static to extremely high frequencies, including space charge fields of moving particles and Particle-In-Cell (PIC) simulations. MAFIA4 is based on the Finite Integration formulation on structured grid and has a modular structure, too. It consists of pre- and postprocessors and several solver modules, including static/stationary fields solver, frequency and time domain solvers in 3D Cartesian and 2D cylindrical coordinates, time domain solvers for coupled field–charges simulations in 3D Cartesian and 2D cylindrical coordinates, eigenmode solver and optimization module. A 64-bit version (MAFIA4.2) is expected to appear soon. An earlier version of MAFIA was used in [17] for analysis of QO launchers.

4.3. High-Frequency Structure Simulator (HFSS)

This is a 3D EM simulation package, initially distributed and supported by Agilent Technologies, nowadays by Ansoft [32] only, which provides old-to-new version converters. It is based on the Finite Element Method (FEM) and uses automatic adaptive mesh generation and refinement, tetrahedral segmentation of the entire space, as well as automatic computing of multiple adaptive solutions until a user defined convergence criterion is achieved. The application fields include analysis of mode dispersion and conversion as well as computation of scattering, impedance and admittance matrices.

4.4. Calabazas Creek Research software development program – Cascade and SURF3D

Cascade is an advanced scattering matrix code for microwave circuit design that may appear to be more accurate and considerably faster than the mesh-based codes [33]. SURF3D (Surface Integral Equation Analysis of QO Launchers), a program still under development, is intended to precisely model the surface fields and to facilitate the synthesis of optimized antennas. It is based on an exact integral formulation of Maxwell’s equations and uses the Multi Level Fast Multipole Algorithm to reduce the computational complexity from $N^3$ to $N^{1.5}$ ($N$ is the number of cells), which is a remarkable achievement. An example of SURF3D usage in QO mode converter optimization is demonstrated on figure 5 [33].

5. Conclusions

In this review, we have briefly sketched the basic features of QO mode converters, the physical and mathematical base they have been treated on, some numerical schemes used, as well as several free and commercially available software packages that might be useful in solving QO related problems. The QO mode converters currently under development are characterized by reduced size and rather complicated geometry. The main goals, notably increasing conversion efficiency, reducing diffraction losses and minimizing side-lobes, require careful choice of physical models and impose hard requirements on the accuracy and efficiency of the computation and simulation software.
The comparative critical analysis of the known approaches indicates that an advantageous strategy for the development of the next generation 3D CAD tools for analysis, design and optimization of high performance QO mode converters should be centered around the following basic characteristics: (i) utilization of adequate physical models based on the coupled mode and vector diffraction theories as well as appropriate exact integral formulations of Maxwell’s equations; (ii) implementation of highly efficient and economical (with respect to the required computational resources) numerical methods, similar to those used in the surface integral equation analysis; (iii) adoption of advanced programming technologies and specialized environments (frameworks) for creation of well structured and extensible software packages that are portable to different platforms, including parallel supercomputers, clusters and grids. This review marks the initial stage of the work on a research project with the aim to develop models and simulation tools that meet the abovementioned requirements.

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