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Design of a Vlasov mode converter of 263 GHz gyrotron oscillator for DNP-NMR

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Abstract: This paper presents design and simulation of a quasi-optical mode converter of 263 GHz gyrotron oscillator operating in the circular TE_{03} mode for dynamic nuclear polarisation enhanced nuclear magnetic resonance (DNP-NMR). The converter consists of a Vlasov stepped-cut launcher, and additional wave beam-shaping reflectors, including an elliptical reflector and a parabolic reflector. First, the preliminary parameters of the launcher are designed with the geometric optics theory. Next, both geometric optics and vector diffraction theory are used to simulate the propagation of wave beam in the mode converter system. Finally, operation of the mode converter was simulated, based on the physical model of Vlasov mode converter for 263 GHz TE_{03} mode gyrotron oscillator. The simulated results show that a good fundamental Gaussian mode is converted at the output window from the TE_{03} mode, and that the power conversion efficiency and the vector correlation are 90.11 and 85.23%, respectively.

1 Introduction

The gyrotron oscillators are a fast-wave device based on the electron cyclotron maser instability, which are capable of producing efficient coherent high power in millimetre and sub-millimetre wave regions [1]. They have been widely applied in the field of thermonuclear fusion, active denial system, material processing, dynamic nuclear polarisation enhanced nuclear magnetic resonance (DNP-NMR) and so on. The typical configuration of a gyrotron oscillator is shown in Fig. 1 [2]. A magnetron injection gun emits an annular beam of electrons, which is guided by an axial magnetic field, after the electrons are transferred to an radio frequency (RF) wave in interaction cavity, finally, the beam is collected on the surface of collector while the RF wave is transformed into a fundamental Gaussian field distribution by quasi-optical (QO) mode converter.

DNP experiments are now recognised as powerful methods of NMR spectroscopy, DNP can greatly improve the sensitivity of NMR spectra, and reduce the acquisition time in NMR experiments. As DNP-NMR experiments move to higher magnetic fields, among various types of THz sources developed in recent years, gyrotron oscillators are one of the most important devices that can reliably generate high power for DNP-NMR experiments at terahertz range.

At present, the output modes of the gyrotron oscillators are usually TE_{mn} high-order waveguide modes. These TE_{mn} modes are inconvenient for direct use and difficult to transmit either, it is necessary to use QO mode converter to transform the high-order waveguide mode into a fundamental Gaussian field distribution [3]. Fig. 2 shows the schematic diagram of the circularly polarised TE_{03} mode Vlasov mode converter; it consists of a stepped-cut launcher, an elliptical reflector and a parabolic reflector. The QO mode converter is thought to be highly efficient and an available method to transform the original waveguide mode into Gaussian mode [4].

2 Theory of geometric optical

When a Vlasov mode converter is designed, the geometric optics approximation of waveguide mode was used. As the launcher diameter and the step-cut length are further larger compared to the free-space wavelength in high-order mode gyrotron oscillator, the geometric optics model provides enough accuracy to warrant its use in the preliminary design of the Vlasov mode converter.

The geometric optics principle of waveguide modes can be derived by starting with the equations of cylindrical waveguide, for a TE_{03} mode, the magnetic fields travelling in the z-direction can be written in cylindrical coordinates as [5–8]

$$H_z(r, \phi, z) = A_{mn} J_m(k_t r) e^{jm\varphi} e^{jk_z z} \tag{1}$$

where A_{mn} is a constant which represents the amplitude of the field, $k_t = x_{mn}/r_w$ and $k_z = \sqrt{k_0^2 - k_t^2}$ are the radial and longitudinal wave numbers, respectively, k_0 is the free-space wave number, J_m represent the m-order Bessel function, r_w is the radius of the launcher. According to the theory of standing wave and Hankel function, we can obtain the angle between the wave vector and the θ-axis as follows:

$$\theta = \arccos(m/x_{mn}) \tag{2}$$

The ray propagates at the Brillouin angle ψ relative to the waveguide axis

$$\psi = \arctan\left(\frac{k_t}{k_z}\right) = \arcsin\left(\frac{k_t}{k_0}\right) \tag{3}$$

The distance that a ray has propagated in the axial direction between two subsequent reflections from the waveguide wall is

$$L_B = 2r_w \cot\theta \tag{4}$$

Applying the geometric optics approximation of the rays, we can obtain that the optimal radiation direction requires the waveguide stepped-cut section length of launcher to meet

$$L_c \geq L_B = 2r_w \cot\theta \tag{5}$$

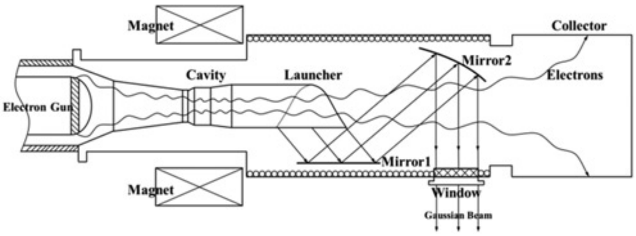

Fig. 1 *Typical structure of the gyrotron oscillator*

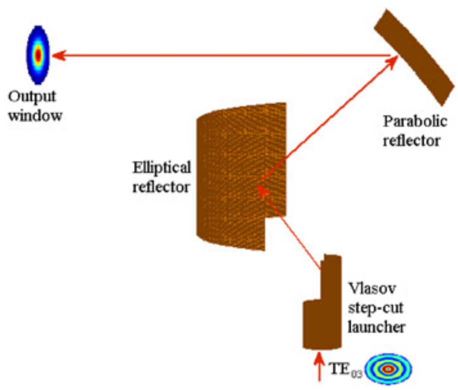

Fig. 2 *Schematic diagram of the circularly polarised TE_{03} mode Vlasov mode converter*

3 Theory of vector diffraction

The vector diffraction theory is used to analyse the operation of the QO mode converter. The observation field radiated from the Vlasov launcher can be done by using the Stratton-Chu formula [7–9]

$$\boldsymbol{E}(\boldsymbol{r}) = \int_{\Omega} \left[-\mathrm{j}\omega\mu(\boldsymbol{n} \times \boldsymbol{H}_{\Omega})G + (\boldsymbol{n} \times \boldsymbol{E}_{\Omega}) \times \nabla G + \boldsymbol{n} \cdot \boldsymbol{E}\nabla G\right] \mathrm{d}\Omega$$
$$\boldsymbol{H}(\boldsymbol{r}) = \int_{\Omega} \left[\mathrm{j}\omega\varepsilon(\boldsymbol{n} \times \boldsymbol{E}_{\Omega})G + (\boldsymbol{n} \times \boldsymbol{H}_{\Omega}) \times \nabla G + (\boldsymbol{n} \cdot \boldsymbol{H}_{\Omega})\nabla G\right] \mathrm{d}\Omega \tag{6}$$

where μ is the permeability, ε is the permittivity and G is the point source Green's function, defined by

$$G(r, r') = \frac{\mathrm{e}^{\mathrm{j}kR}}{R} \tag{7}$$

where $R = |r - r'|$ is the distance between the observation point and the source point. The primed variables indicate a source point and the unprimed variables indicate an observation point.

It should be noted that the radiation characteristic of the Vlasov launcher, consisting of a smooth waveguide and a stepped-cut, could be analysed using the proposed method directly in detail since there is only one operating mode.

According to the Stratton-Chu formula, we can obtain the field of circular aperture and Vlasov stepped-cut launcher, and combining the boundary condition and geometric optical method, the initial current distribution on the circular aperture and Vlasov stepped-cut launcher could be calculated according to the radiation field, which can be written as [4, 9]

$$\boldsymbol{J} = 2(\boldsymbol{n} \times \boldsymbol{H}) \tag{8}$$

Meanwhile, according to the radiation field, power efficiency can be obtained by the power flux of output window, which can be written as

$$P = \iint_S \frac{1}{2}\mathrm{Re}\left(\boldsymbol{E} \times \boldsymbol{H}^*\right)\mathrm{d}\boldsymbol{S} \tag{9}$$

The wave beam quality is usually described as the correlation coefficient of the wave beam to an ideal fundamental Gaussian mode. There are two ways to define the correlation coefficient: the scalar Gaussian contents η_s of the wave beam, which is defined as the amplitude correlation of the field to an ideal Gaussian distribution, and the vector Gaussian content η_v including amplitude and phase, which can be given as [8, 10]

$$\eta_s = \frac{\iint_s |u_1| \cdot |u_2| \mathrm{d}s}{\sqrt{\iint_s |u_1|^2 \mathrm{d}s \cdot \iint_s |u_2|^2 \mathrm{d}s}} \tag{10}$$

$$\eta_v = \frac{\iint_s |u_1| \cdot |u_2| \exp[\mathrm{j}(\varphi_1 - \varphi_2)]\mathrm{d}s \cdot \iint_s |u_1| \cdot |u_2| \exp[\mathrm{j}(\varphi_2 - \varphi_1)]\mathrm{d}s}{\sqrt{\iint_s |u_1|^2 \mathrm{d}s \cdot \iint_s |u_2|^2 \mathrm{d}s}} \tag{11}$$

where $|u_1| \cdot \exp(\mathrm{j}\varphi_1)$ represents the field distribution of wave beam at the output window and $|u_2| \cdot \exp(\mathrm{j}\varphi_2)$ an ideal fundamental Gaussian distribution, respectively.

4 Reflect mirror system

The purpose of the reflect mirror system is to transform the launched wave beam to the desired fundamental circular Gaussian wave beam with appropriate waist. The structure of a Vlasov-type converter, shown in Fig. 3, consists of a step-cut waveguide launcher and two focusing reflectors, which direct the radiation to a small, Gaussian focus [7].

The first mirror is an elliptical reflector, which function is to focus the wave beam from launcher in a horizontal direction, then radiate to the second mirror, which is a parabolic reflector, and function is to focus the wave beam from launcher in a vertical direction. Fig. 4 shows plots of the cross-sectional view of a step-cut launcher and two focusing reflectors.

The elliptical reflector function can be written as

$$\frac{(y - c_2/2)^2}{a^2} + \frac{x^2}{b^2} = 1 \tag{12}$$

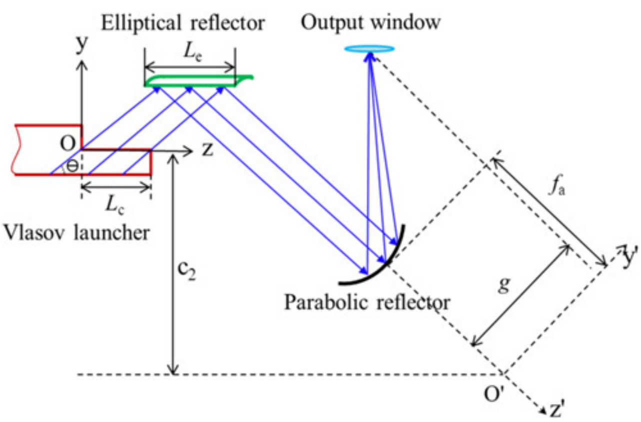

Fig. 3 *Schematic diagram of the circularly polarised mode Vlasov mode converter*

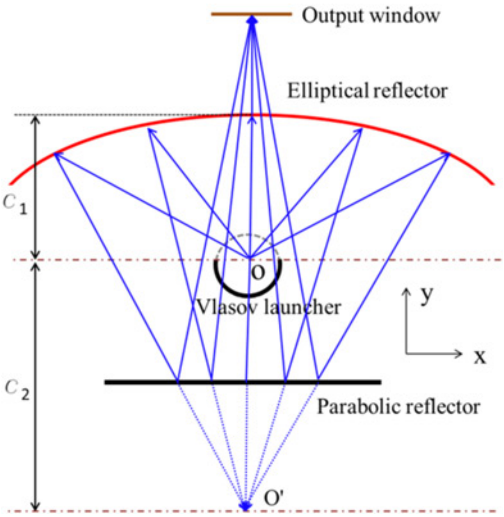

Fig. 4 *Cross-sectional view of a step-cut launcher and two focusing reflectors*

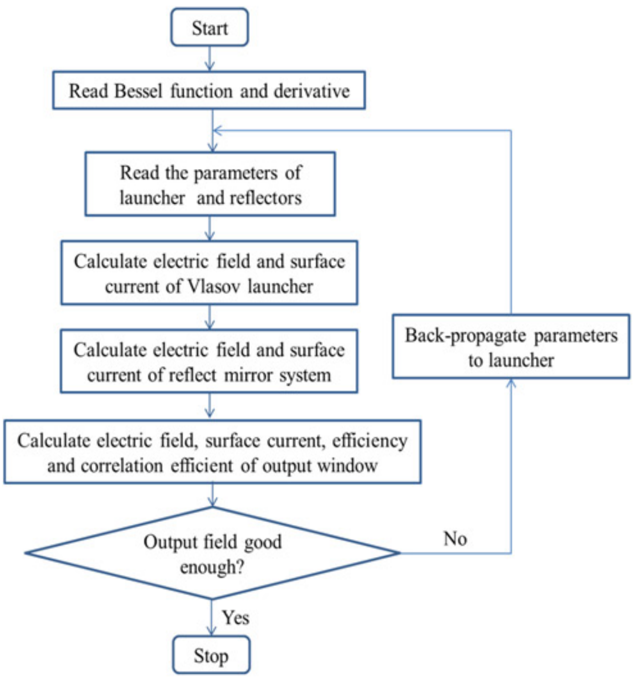

Fig. 5 *Flowchart showing the major steps of the Vlasov mode converter*

where parameters a and b are length of long and short axis, respectively, c_2 is focal length of the elliptical reflector.

For the parabolic reflector, the function may be expressed as follows:

$$(y' - g)^2 = -4f_a(z' + f_a) \tag{13}$$

where parameter f_a is focal length of the parabolic reflector.

5 Design and simulation of Vlasov mode converter

Based on the geometric optics theory and vector diffraction theory, the fields on each reflector surface can be obtained. A code is programmed to design the Vlasov mode converter through numerical calculation.

Simulations are initiated by using the code to obtain the parameters, simulate the launch, reflection and propagation of wave beam through the Gaussian optics mirror transmission system. First, it is necessary to relate the required parameters in the Vlasov mode converter, including radius of the launcher r_w, direction angle θ, cut length L_c, elliptical reflector length L_e, elliptical reflector focal length c_2, parabolic reflector focal length f_a and so on. Finally, the Vlasov mode converter is optimised using the code, the electric field distribution of the mode converter can be determined. The algorithm used for the design of mode converter can be

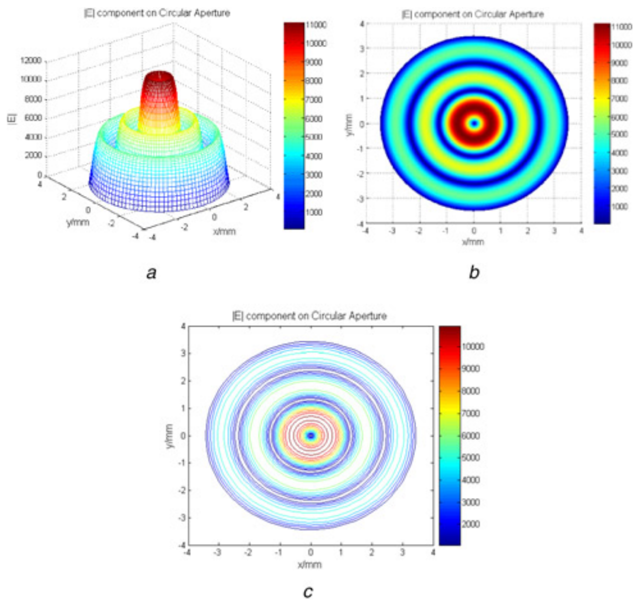

Fig. 6 *Electric field distribution of TE_{03} mode at the circular aperture*
a 3D
b 2D
c Contour

Table 1 Design parameters of the Vlasov mode converter for a 263 GHz gyrotron oscillator

Parameter	Value	Parameter	Value
frequency	263 GHz	mirror 2 focal length f_a	65 mm
operating mode	TE_{03}	mirror 1 length (z size) L_e	51.4 mm
launcher radius r_w	3.5 mm	mirror 1 width (x size) W_e	45 mm
direction angle θ	90°	mirror 2 length (z size) L_p	25.5 mm
Brillouin angle ψ	31.83°	mirror 2 width (x size) W_p	25 mm
cut length L_c	16.9 mm	mirror 1 centre position	(0, 9.5 mm, 25.7 mm)
output window radius r_o	12.7 mm	mirror 2 centre position	(0,–18.9 mm, 64.1 mm)
mirror 1 focal length c_2	22 mm	window centre position	(0, 24 mm, 64.1 mm)

succinctly summarised by the flow diagram in Fig. 5. Table 1 summarises the final design parameters for the mirror relay and the characteristics of the desired output wave beam of a 263 GHz gyrotron oscillator for DNP-NMR. All positions are specified in the launcher coordinate system.

Figs. 6–9 show the simulated electric field or surface current at circular aperture, Vlasov stepped-cut launcher, elliptical reflector

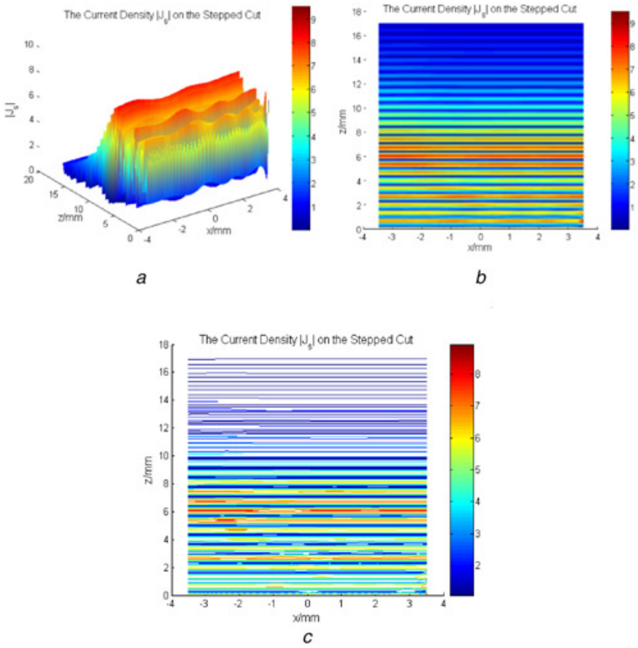

Fig. 7 *Surface current distribution at Vlasov stepped-cut launcher*
a 3D
b 2D
c Contour

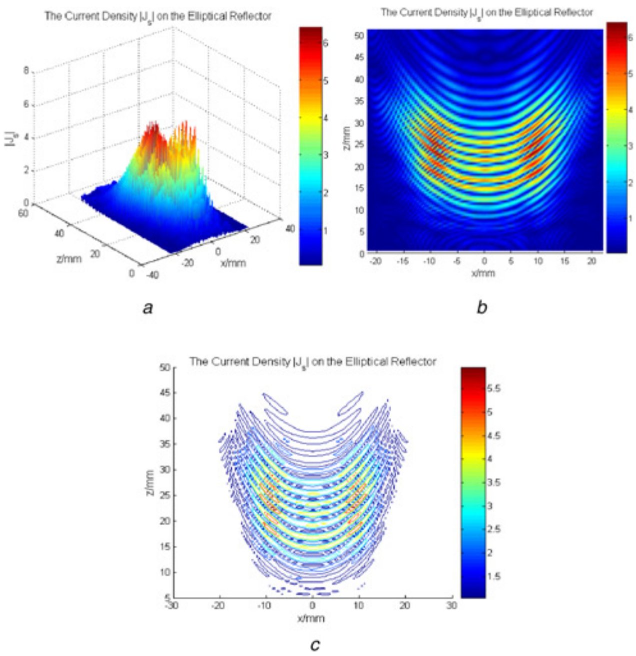

Fig. 8 *Surface current distribution at the elliptical reflector*
a 3D
b 2D
c Contour

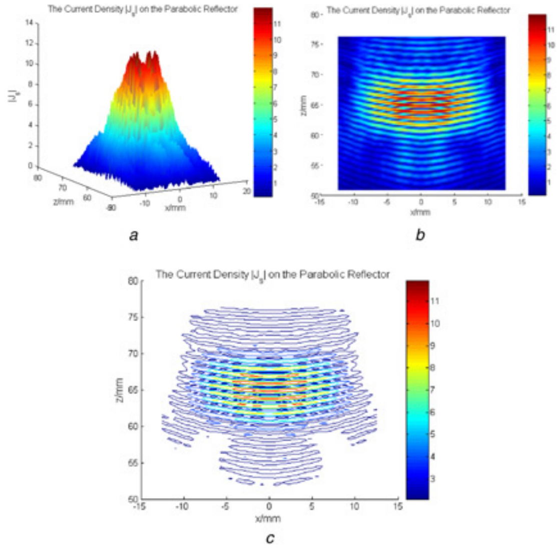

Fig. 9 *Surface current distribution at the parabolic reflector*
a 3D
b 2D
c Contour

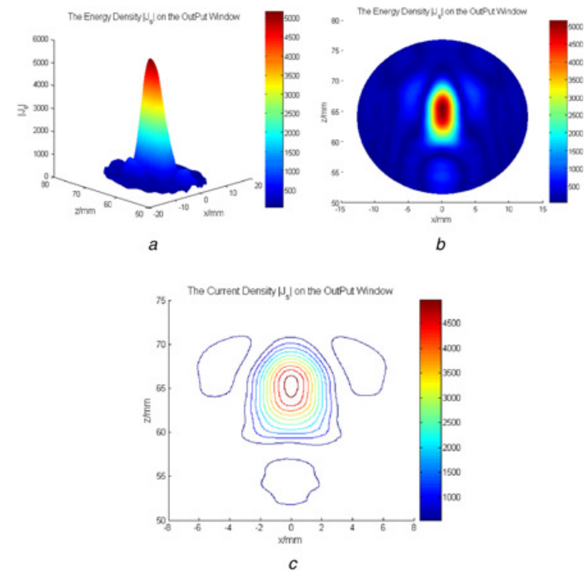

Fig. 10 *Electric field distribution at the output window*
a 3D
b 2D
c Contour

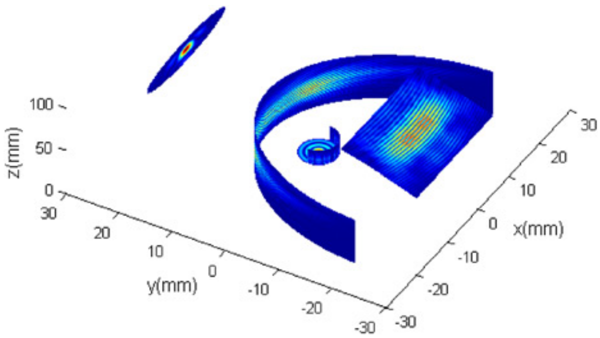

Fig. 11 *Electric field-strength distributions of the Vlasov mode converter system*

Table 2 Power efficiency of every part of Vlasov mode converter

	Circular aperture	Launcher	Elliptical reflector	Parabolic reflector	Output window
power, W	1	0.984	0.969	0.945	0.9011
efficiency, %	100	98.4	96.9	94.5	90.11

and parabolic reflector, respectively. Fig. 10 gives the electric field distribution on output window. The electric field-strength distribution of the Vlasov mode converter system is shown in Fig. 11. From the figures, the good Gaussian mode is obtained and the numerical calculation result gives the QO converter that can generate a scalar correlation coefficient of 92.05%, a vector correlation coefficient of 85.23% and a power efficiency of 90.11%. Final power efficiency of every part of Vlasov mode converter are summarised in Table 2. The waist of Gaussian mode in the output window is 4 mm × 7.5 mm.

6 Conclusion

In this work, we have presented the results of a study to design a Vlasov mode converter of 263 GHz TE_{03} mode gyrotron oscillator for DNP-NMR based on the geometric optics and vector diffraction theory. The Vlasov mode converter consists of a Vlasov launcher and two reflector mirrors. The detailed characteristics of the geometric optics theory, vector diffraction theory and reflect mirror systems were described. Results of numerical simulations show that the mode converter can generate a scalar correlation coefficient of 92.05%, a vector correlation coefficient of 85.23% and a power efficiency of 90.11%.

7 Acknowledgment

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