Effect of Magnetic Field on Self-focusing and Stimulated Raman Scattering of q-Gaussian Laser Beam in Plasma

Ahmed S. Ahmed
Hyder A. Salih
Khaleel I. Hassoon

Department of Applied Sciences, University of Technology, Baghdad, IRAQ

This paper delves into relativistic q-Gaussian laser beam self-focusing effects on stimulated Raman scattering (SRS) in magnetized plasma. Analytical solutions for nonlinear coupled wave equations defined by pump and electron plasma wave (EPW) for scattered waves were obtained using variational theory. We ran a numerical analysis on the resulting equations to determine how the laser and plasma properties affect the pump beam dynamics and the intensity of the scattered waves. The pump beam's self-focusing action greatly affects the dispersed wave's strength. Our research also shows that the stimulated Raman scattering effect increases as the self-focusing impact increases. The stimulated Raman scattering yield was analyzed with respect to several parameters, such as plasma density, q-value, and the influence of the magnetic field. The main effect is that when q increases, so do the SRS fluctuations; similarly, as plasma density and magnetic field concentration rise, the SRS fluctuations rise too. We can see that the pump beam's self-focusing significantly affects the plasma's reflectivity of SRS since the reflectivity decreases with rising q-value, density, and magnetic field values.

Keywords: Self-focusing; q-Gaussian; Stimulated Raman scattering; Magnetized plasma
Received: 14 March 2024; **Revised:** 25 April 2024; **Accepted:** 02 May 2024

1. Introduction

Stimulated Raman forward scattering (SRS) [1-6] is an important nonlinear process in the laser–plasma accelerator and fast igniter fusion scheme. In light scattering, electrons are the primary agents as a beam moves from one medium to another. The mobility of the nuclei is another factor that may affect the scattering of light [7]. This leads to Raman and Brillouin scattering, which occurs when the frequency of the propagating light varies in a manner that depends on the mobility of the nuclei. These values are the optical and acoustic phonon frequencies of Raman and Brillouin scattering, respectively [8]. If the intensity of the light beam that is passing is too high, the light that was originally scattered might induce more scattering of the light that is passing, ultimately resulting in a large rise in the intensity of the dispersed light [9]. This particular sort of scattering is referred to as stimulated scattering, and it occurs when light that was first dispersed boosts later scattering effects. There are both theoretical and practical uses for Raman scattering, making it an intriguing issue in nonlinear optics [10-12]. In 1962, when investigating ruby laser Q-switching with a nitrobenzene Kerr cell, Woodbury and Ng [11,12] discovered the stimulated Raman effect. The Kerr cell was found to be emitting strong infrared light.

The physics of stimulated Raman scattering in plasmas can be illustrated by considering the effect of laser beam with powerful energy (E_0) on a plasma that has fluctuations in its density along the $\vec{k}_0$ direction of the incident beam. These density fluctuations result from the propagation of EPW in the plasma. When the laser beam meets the plasma, it causes the electrons to vibrate due to the beam's electric field, generating a transverse current (J_T). If the wave vectors and frequencies are identical, the incident current creates a scattered wave with strength (E_S). The scattered wave interacts with the incident laser beam, causing changes in wave pressure. These changes in wave pressure move electrons from high to low-pressure areas. This increases the disturbance in density, enhancing the initial density fluctuations associated with the EPW, i.e., strengthening the plasma wave. This reactive process results in stimulated Raman scattering or instability [13,14].

SRS is a coherent Raman scattering phenomenon that gives up to 10^7 times amplification compared to spontaneous Raman scattering. It occurs when energy is transferred from a high-energy beam (pump beam) to a low-energy beam (probe beam) [15,16].

Numerous fields, including particle acceleration and laser-induced fusion, actively investigate ways to couple high-power laser beams with plasma more effectively. Stimulated Brillouin scattering (SBS), self-focusing, filamentation, two-plasmon decay, stimulated Raman scattering (SRS), and other instabilities are introduced into the laser-plasma interaction process [17-19]. Stimulated Raman Scattering (SRS) in the context of ICF is a phenomenon in which the incident laser, upon resonance with the fundamental mode of the plasma, decays into an electromagnetic wave (EW) and EPW. Scattering could occur in either of the three ways: (1) Backscattering, where the scattered EW traverses back and combines with the incoming laser, further driving the EPW resulting in the growth of its amplitude, increasing its scattering efficiency of the plasma (as the EPW denotes the natural fundamental mode of the plasma). This unstable feedback loop thus created causes SRS to grow exponentially, decreasing the effective energy deposition on the fusion fuel. Also, the scattered beams affect the illumination symmetry, which not only interferes with the efficient coupling of laser energy, but also induces tremendous growth in hydrodynamic instabilities. (2) Forward scattering, where the laser is scattered in the forward direction, resulting in formation of supra-thermal electrons of energies >10keV, causing preheat of the fusion fuel. (3) Side-scattering, where the SRS convects away from the source, inducing disturbances at farther regions in space [19-21]. Singh and Sharma [21] conducted a study on the stimulation of excitation of EPW in the presence of a laser beam with blank intensity at the centre. The concentration of hollow Gaussian beam (HGB), EPW stimulation, and back reflection of HGBs were explored. These results appear to find applications in the field of laser-induced fusion schemes, especially when higher modes are present in the laser beam. Gupta et al. [22] analyzed the reference system for lasers with elliptical q-Gaussian distribution in uniaxially inhomogeneous plasmas. The effect of laser beam self-focusing on the power of the scattered wave has been explored in detailed manner. Walia et al [23] discovered the existence of a self-focusing beam in stimulated Raman scattering (SRS) in collisional plasmas. In this context, nonlinear collisions arise as a result of nonuniform heating, which leads to carrier redistribution. The plasma density profile is adjusted in a direction perpendicular to the main beam axis. Ahmed and his colleagues [24] studied the occurrence of polarized radiation emission (SRS) when a q-Gaussian laser beam propagates through a non-magnetized plasma. The study showed that increasing the q value led to an increase in SRS throughput, as well as an increase in laser beam intensity and plasma density. The results also showed that the value of the integrated reflection was affected by the increase in the value of q, as its value increased with an increase in q and the growth rate.

Many researchers have studied self-focusing [25-28] and its effect on the stimulated Raman scattering, but few have studied its effect on the stimulated Raman scattering for q-Gaussian laser. This study used the paraxial approach method, which gave results different in some aspects from the previous work.

The current study thoroughly investigates the SRS of a q-Gaussian laser beam in magnetized plasma. Relativistic nonlinearity and its role in the creation of plasma waves are examined in the Section II. The analytical and numerical investigation of the relativistic self-focusing of a q-Gaussian laser beam is carried out in Section III. Section IV of the study examines and discusses the impact of relativistic nonlinearity and diffraction processes on the beamwidth parameters of both the pump and scattered beams and their effects on SRS. Finally, section V presents the conclusions.

2. Nonlinear permittivity tensor

Consider a uniform plasma of equilibrium electron density (n_0^0), immersed in a magnetic field $\vec{B}_0 \| \hat{y}$. An intense laser beam propagates through it along $\hat{z}$ direction,

$$\vec{E} = \vec{A} e^{-i(\omega t - kz)} \tag{1}$$

where $\vec{A} = \hat{x} A_x + \hat{z} A_z$

The response of plasma electrons is governed by the relativistic equation of motion,

$$m \frac{\partial}{\partial t}(\gamma_0 \vec{v}) + m \cdot \vec{\nabla}(\gamma_0 \vec{v}) = -e\vec{E} - \frac{e}{c} \vec{v} \times \vec{B}_0 \tag{2}$$

Where m is the rest mass, $-e$ is the electronic charge, c is the speed of light in a vacuum, and γ_0 is the Lorentz factor where gives by:

$$\gamma_0 = \left(1 + \frac{e^2 E_0^2}{m^2 \omega^2 c^2}\right)^{1/2} \tag{3}$$

For ω frequency response this equation reduces to

$$-i\omega\gamma_0 \vec{v} = -\frac{e\vec{E}}{m} + \vec{v} \times \vec{\omega}_{co}$$

giving

$$\vec{v} = -\frac{e(i\omega\vec{E} + \vec{E} \times \vec{\omega}_{c0}/\gamma_0)}{m\gamma_0(\omega^2 - \omega_{c0}^2/\gamma_0^2)} \tag{4}$$

where $\vec{\omega}_{c0} = \frac{e\vec{B}_0}{mc}$ and $\gamma \cong 1 + |v|^2/4c^2$

The permittivity tensor that it is composed of the following components [28]:

$$\varepsilon_{xx} = 1 - \frac{\omega_p^2}{(\omega^2 - \omega_c^2)} \tag{5}$$

$$\varepsilon_{xx} = \varepsilon_{yy} \tag{6}$$

$$\varepsilon_{xy} = i \frac{\omega_p^2}{\omega} \left(\frac{\omega_c}{\omega^2 - \omega_c^2}\right) \tag{7}$$

$$\varepsilon_{yx} = -i \frac{\omega_p^2}{\omega} \left(\frac{\omega_c}{\omega^2 - \omega_c^2}\right) \tag{8}$$

The intensity-dependent dielectric constant of the plasma is given by:

$$\varepsilon = \varepsilon_0 + \phi(E_z E_z^*) \tag{9}$$

where

$$\phi = \frac{\omega_{p0}^2}{\omega^2} \left(1 - \frac{1}{\left(1 + \frac{e^2 E_0^2}{m^2 \omega^2 c^2}\right)^{1/2}}\right) \tag{10}$$

The effective non-linear permittivity may be determined by using the following formula:

$$\varepsilon = \varepsilon_f + \beta \frac{r^2}{r_0^2} \tag{11}$$

where the values of ε_f and β are given by the following relationships:

$$\varepsilon_f = 1 - \frac{\omega_{p0}^2}{\omega^2} \left[1 + \frac{\alpha A_{00}^2}{f^2}\right]^{-\frac{1}{2}} \tag{12}$$

$$\beta = -\frac{\omega_{p0}^2}{\gamma \omega^2} \left[\frac{\omega_{c0}^2}{\omega^2} + \frac{\alpha A_{00}^2}{2\gamma^2 f^4}\right] \tag{13}$$

3. Relativistic Self-focusing

We study the possibility of propagating a high-energy q-Gaussian laser beam within a collisionless plasma, along the z-direction. The initial intensity distribution of the beam is determined by [28]:

$$E_0 E_0^* = A_{00}^2 \left[1 + \frac{r^2}{q {r_0}^2}\right]^{-q} \tag{14}$$

The wave equation is the prevailing equation that governs the electric field of a laser beam in a plasma [28]:

$$\nabla^2 \mathrm{E}_0 - \nabla\left(\nabla \cdot \vec{E}_0\right) + \frac{\omega_0^2}{c^2}\hat{\varepsilon_0} \cdot \vec{E}_0) = 0 \qquad (15)$$

The symbol $\hat{\varepsilon_0}$ is the permittivity tensor. When an electric field is given by:

$$\vec{E}_0 = \vec{A}(x, y, z)\exp\{i(\omega_0 t - k_0 z)\} \qquad (16)$$

$\vec{A}(x, y, z)$ represents the laser beam's amplitude field which a function of (x,y,z). Continuing with this assumption, $\vec{A}(x, y, z)$ might vary as:

$$\vec{A}(x, y, z) = \vec{A}_0 \ \exp\{-ik_0 S_0(x, y, z)\} \qquad (17)$$

For a q-Gaussian beam $\vec{A}_0$ and S_0 are defined as follows:

$$A_0^2(r, z) = \frac{A_{00}^2}{f^2(z)}\left[1 + \frac{r^2}{\mathrm{q} r_0^2 f^2(z)}\right]^{-q} \qquad (18)$$

$$S_0 = \frac{1}{2}r^2\frac{1}{f}\frac{df}{dz} + \Phi_0(\mathrm{z}) \qquad (19)$$

In this context, f stands for the beam width and r_0 is the spot size parameter. After dividing the real and imaginary parts of the resultant formula, the following set of equations is formed by inserting Eq. (18) into Eq. (15). Additionally, in Eq. (15), the actual part is:

$$2\frac{\partial S}{\partial z} + \left(\frac{\partial S}{\partial r}\right)^2 = \frac{1}{k^2 A_{20}}\left(\frac{\partial^2 A_{20}}{\partial r^2} + \frac{1}{r}\frac{\partial A_{20}}{\partial r}\right) + \frac{\omega^2 \varepsilon}{c^2 k^2} \quad (20)$$

The equation controlling the bandwidth parameter f is obtained using Eqs. (4) and (7) in Eq. (6). In addition, the r^2 coefficient equation is used on both sides of the derived formula:

$$\frac{d^2 f}{d\zeta^2} = \frac{1}{f^3}\left(\frac{q+2}{q}\right) + \frac{\omega^2 r_0^2}{c^2}\left(-\frac{\omega_{p0}^2}{\gamma\omega^2}\left[\frac{\omega_{c0}^2}{\omega^2} + \frac{\alpha A_{00}^2}{2\gamma^2 f^4}\right]\right) f \quad (21)$$

The fourth-order Runge-Kutta method was used to solve Eq. (21), which describes the laser and plasma parameters at variable levels. The problem is that an analytical solution is not possible. The vacuum wavelength of the laser beam is determined as 1.053 µm, and the original laser radius is r_0 = 10 µm due to the intensity of the laser beam (I=10^{18} W/cm^2).

Figure (1) shows, for different values of the q-parameter, the changes in the laser beamwidth parameter f concerning the normalized propagation distance ξ. For instance, self-focusing becomes more effective as q increased.

Figures (2) and (3) show how f changes with ζ, where figure (2) shows the relation when q=10 for four different values of $\omega_{\mathrm{p0}}^2/\omega^2$. From the figure, we see that increasing $\omega_{\mathrm{p0}}^2/\omega^2$ leads to improved self-focusing, which reduces the self-focusing length. We also note that increasing the plasma density increases the power and speed of self-focusing.

Figure (3) shows how the beamwidth parameter changes with propagation distance for the parameters $\omega_{\mathrm{p0}}^2/\omega^2 = 0.02$ and $\alpha A_{00}^2 = 1.2$ and $q = 10$. When the laser beam is stronger, the self-focus increases. In this case, the self-focus length decreases with the propagation distance due to the increasing value of the magnetic field. When the magnetic field is stronger, the self-focusing length becomes shorter than the previous form. The focus effect also becomes more intense.

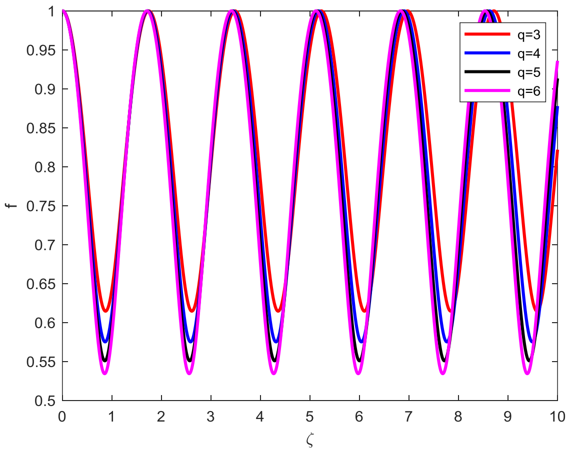

Fig. (1) Effect of the q value on the graph between of the beam width of the laser beam with propagating distance through the plasma for the fixed value of the $\omega_{p0}^2/\omega^2 = 0.02, \omega_{c0}^2/\omega^2 = 0.3$ and $\alpha A_{00}^2 = 1.2$

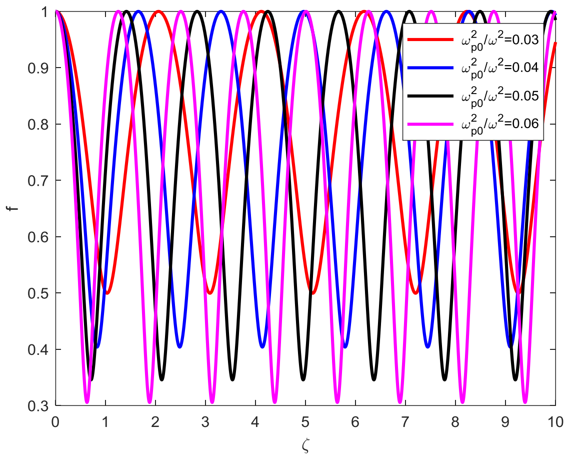

Fig. (2) Effect of the plasma density on the graph between of the beam width of the laser beam with propagating distance through the plasma for the fixed value of the $q = 10, \omega_{c0}^2/\omega^2 = 0.3$ and $\alpha A_{00}^2 = 1.2$

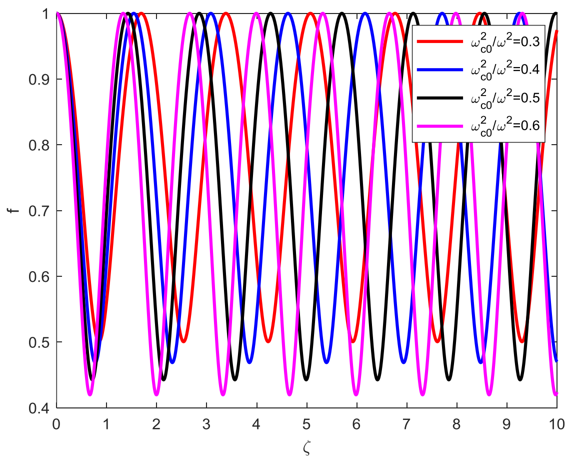

Fig. (3) Effect of the magnetic field on the graph between of the beam width of the laser beam with propagating distance through the plasma for the fixed value of the $q = 10, \omega_{p0}^2/\omega^2 = 0.02$ and $\alpha A_{00}^2 = 1.2$

4. Stimulated Raman Scattering

In plasma, electron waves arise with frequencies (ω) and wavenumbers (k). When these waves interact with a powerful laser beam, SRS waves are emitted with frequencies (ω_s) and wavenumbers (k_s), which can be represented by the relations $\omega_s = \omega - \omega_0$ and $k_s = k - k_0$. Nonlinear interactions between the SRS wave and the laser wave led to attenuation of the laser wave.

The relations $\omega_s = \omega - \omega_0$ and $k_s = k - k_0$ may be used to express the frequencies ω_s and wavenumbers k_s of the SRS waves that are produced when these waves come into contact with a strong laser beam. Laser wave attenuation results from nonlinear interactions between SRS and laser waves. The travelling and consumed lasers are described by the wave equations with the following frequencies (ω_d) and wavenumbers (k_d):

$$\nabla^2 \vec{E}_d + \frac{\omega_d^2}{c^2}\left(1 - \frac{\omega_{p0}^2}{\gamma\omega_d^2}\right)\vec{E}_d + \frac{ie^2\omega_p^2 k|\vec{E}_s\vec{E}_s^*|\vec{E}_d}{16\Gamma_e m_0^2\gamma^3 c^2\omega_d\omega_s^2} = 0 \quad (22)$$

and

$$\nabla^2 \vec{E}_s + \frac{\omega_s^2}{c^2}\left(1 - \frac{\omega_p^2}{\gamma\omega_s^2}\right)\vec{E}_s + \frac{ie^2\omega_p^2 k^2|\vec{E}_d\vec{E}_d^*|\vec{E}_s}{16\Gamma_e m_0^2\gamma^3 c^2\omega_s\omega_d^2} = 0 \quad (23)$$

where

$$\vec{E}_d = \vec{E}_{d0}\exp(i\{\omega_d t - k_d[z + S_d]\})) \quad (24)$$

$$\vec{E}_s = \vec{E}_{s0}\exp(i\{\omega_s t - k_s[z' + S_s]\})) \quad (25)$$

In this equation, Γ_e is the damping coefficient and the other variables have the same usual meaning.

After entering these values into Eqs. (24) and (25) into Eq. (22), and by separating the real and imaginary parts, we obtain a set of related equations. The equation gives us:

$$2\frac{\partial S_d}{\partial z} + \left(\frac{\partial S_d}{\partial r}\right)^2 = \frac{\omega_d^2\varepsilon_d}{c^2k_d^2} + \frac{1}{k_d^2 E_{d0}}\left(\frac{\partial^2 E_{d0}}{\partial r^2} + \frac{1}{r}\frac{\partial E_{d0}}{\partial r}\right) \quad (26)$$

where

$$E_{d00}^2(r,z) = \frac{E_{d20}^2}{f_d^2(z)}\left[1 + \frac{r^2}{qr_0^2 f_d^2(z)}\right]^{-q} e^{-2l_d z} \quad (27)$$

$$S_{d0} = \frac{1}{2}r^2\frac{1}{f_d}\frac{df_d}{dz} + \Phi_d(z) \quad (28)$$

$$E_{s00}^2(r,z) = \frac{E_{s20}^2}{f_s^2(z)}\left[1 + \frac{r^2}{qr_0^2 f_s^2(z)}\right]^{-q} e^{-2l_s z'} \quad (29)$$

By substituting Equations 27 and 28 into Equation 26, one gets the following equation:

$$\frac{d^2 f_d}{d\xi^2} = \frac{q^2}{k^2 f_d^3(r^2/f_d^2 + qr_0^2)^2} + \frac{\alpha E_{d20}^2\omega_p^2}{c^2 f_d^3 k^2 r_0^2}e^{-2l_d z} \quad (30)$$

where f_d and E_{d0} represnts beam width and real function of depletion laser beam, respectively

Additionally, the variation of E_{s0} is presumed to be:

$$E_{s0} = E_{s00}\exp\{-ik_s S_s\} \quad (31)$$

By similar way to get Eq. (31) and assuming that:

$$S_{s0} = \frac{1}{2}r^2\frac{1}{f_s}\frac{df_s}{dz} + \Phi_s(z') \quad (32)$$

and, by separating into real part and imaginary part, one gets the real part as:

$$2\frac{\partial S_s}{\partial z'} + \left(\frac{\partial S_s}{\partial r}\right)^2 = \frac{\omega_s^2\varepsilon_s}{c^2k_s^2} + \frac{1}{k_s^2 E_{s0}}\left(\frac{\partial^2 E_{s0}}{\partial r^2} + \frac{1}{r}\frac{\partial E_{s0}}{\partial r}\right) \quad (33)$$

Substituting Eqs. (29-32) into Eq. (33), and by equating the coefficients of the variable r^2 on the two equation sides, one gets the subsequent equation:

$$\frac{d^2 f_s}{d\xi'^2} = \frac{1}{f_s^{\,3}}\left(\frac{q+2}{q}\right) + \frac{\omega^2 r_0^2}{c^2}\left(-\frac{\omega_{p0}^2}{\gamma\omega^2}\left[\frac{\omega_{c0}^2}{\omega^2} + \frac{\alpha A_{00}^2}{2\gamma^2 f_s^4}\right]\right) f_s e^{-2l_s z'} \quad (34)$$

where

$$l_s = \frac{-e^2\omega_p^2 k^2|E_{d0}|_{r=0}^2}{32 m_0^2\gamma_0^3\Gamma_e c\omega_s^2\omega_d^2\varepsilon_s^{\frac{1}{2}}} \quad (35)$$

The function A_d is a complex function that is dependent on spatial variables. Additionally, it is assumed that the variation of A_d is:

$$E_{d0} = E_{d00}\exp\{-ik_d S_d\} \quad (36)$$

Equation (35) was also solved using numerical methods. Figure (4) shows the relationship between the stimulated Raman scattering and the beamwidth when the q values are changed. It is observed that when q values are less than 3, defocus occurs.

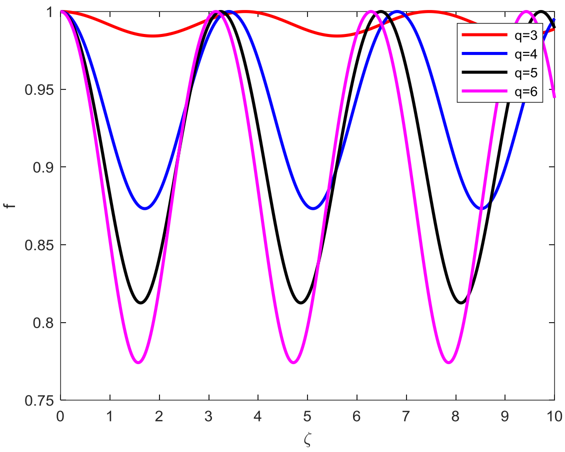

Fig. (4) Effect of the q value on the beam width parameter of the laser beam propagating through the plasma for the fixed value of the $\omega_{p0}^2/\omega^2 = 0.02, \omega_{c0}^2/\omega^2 = 0.3$ and $\alpha A_{00}^2 = 1.2$

Figures (5) shows how the plasma density and magnetic field affects the SRS back scattered of the laser beam. We note that the self-focusing range SRS back scattered of the laser beam improves as the plasma density and magnetic field increases. In Fig. (6), because the laser beam experiences a lower refractive index in the deeper parts of the plasma when the magnetic field is applied, and it helps increase the focus range of the laser beam.

The integrated reflectivity is the ratio between integrated of scatter power to integrated of input power:

$$R = \frac{E_{s20}^2}{A_{00}^2}\frac{r_{s0}}{r_0}e^{-l_s\zeta} \quad (37)$$

By using Eq. (37), as shown in figures (7-9), the integrated reflection with distance ξ. In Fig. (7), maximum back reflection occurs when the central laser beam is aligned with the centers of the q-Gaussian beam. It was also observed that the reflectivity decreases as the value of q in the array increases, because the density of q-Gaussian decreases as the beam size increases.

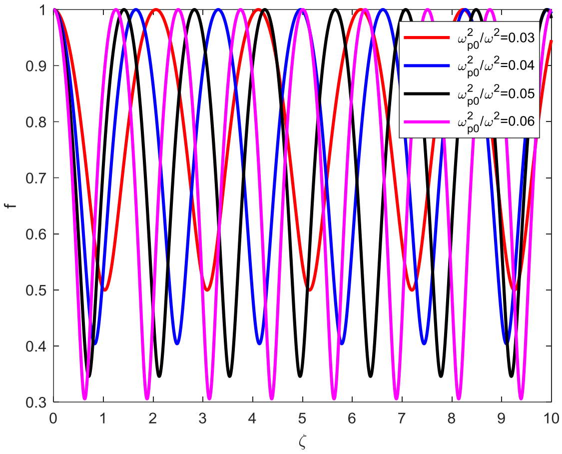

Fig. (5) Effect of the plasma density on the graph between back SRS and the beam width of the laser beam propagating through the plasma for the fixed value of the $q = 10, \omega_{c0}^2/\omega^2 = 0.3$ and $\alpha A_{00}^2 = 1.2$

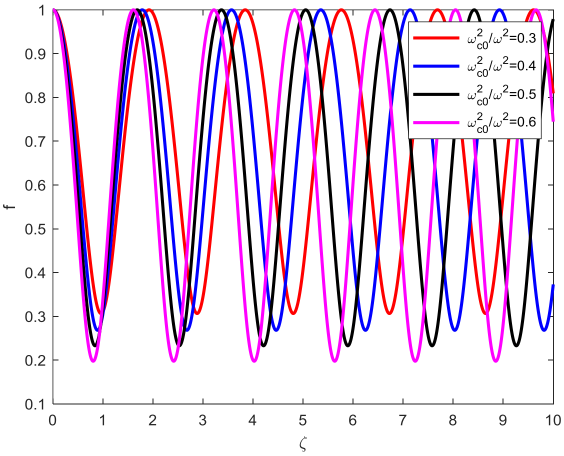

Fig. (6) Effect of the magnetic field on the graph between back SRS and the beam width of the laser beam propagating through the plasma for the fixed value of $q = 10, \omega_{p0}^2/\omega^2 = 0.02$ and $\alpha A_{00}^2 = 1.2$

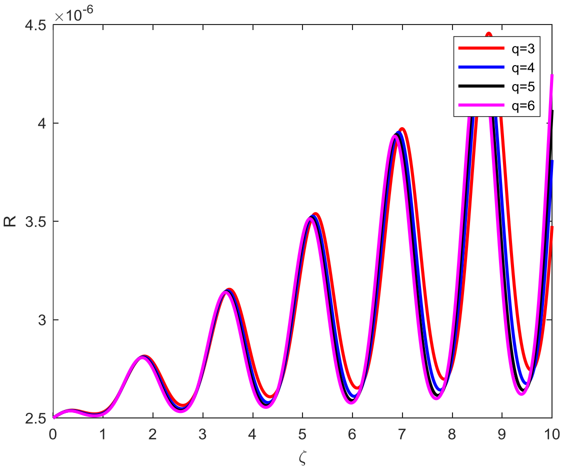

Fig. (7) Effect of the q-value on the evolution of the stimulated Raman reflectivity of the plasma for the fixed value of the $\omega_{p0}^2/\omega^2 = 0.02, \omega_{c0}^2/\omega^2 = 0.3$ and $\alpha A_{00}^2 = 1.2$

Figure (8) shows how reflectivity is affected by increasing plasma density. It can be seen that the reflectivity decreases as the density increases. This is because the plasma becomes more self-concentrated as the rate of change of the plasma density increases. Figure (9) shows the effect of increasing magnetic field on reflectivity. It is shown that the reflectivity decreases with increasing magnetic field. This is because the self-focusing length becomes shorter as the magnetic field strength increases.

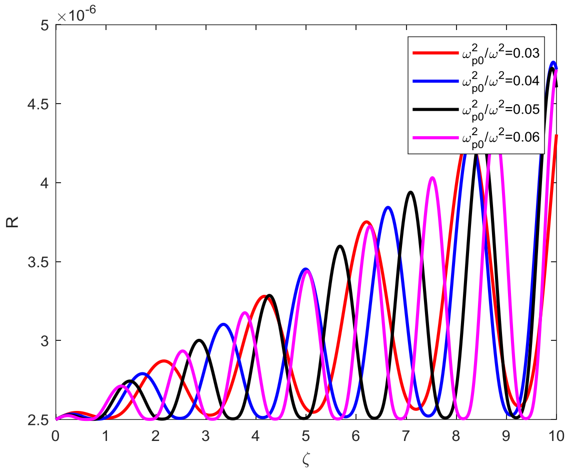

Fig. (8) Effect of the plasma density on the evolution of the stimulated Raman reflectivity of the plasma for the fixed value of the $q = 10, \omega_{c0}^2/\omega^2 = 0.3$ and $\alpha A_{00}^2 = 1$.

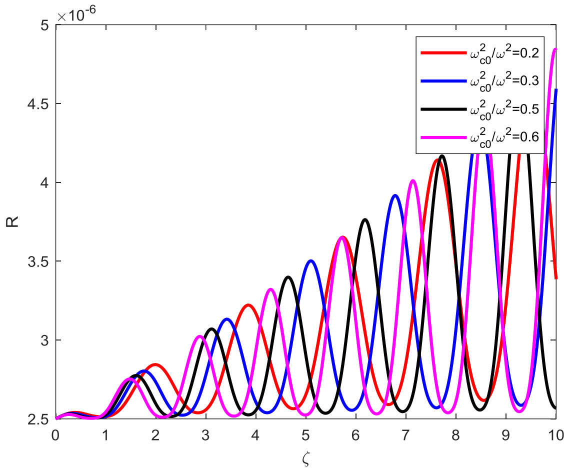

Fig. (9) Effect of the magnetic field on the evolution of the stimulated Raman reflectivity of the plasma for the fixed value of the $q = 10, \omega_{p0}^2/\omega^2 = 0.02$ and $\alpha A_{00}^2 = 1.2$

5. Conclusions

This study addresses the case of SRS when a q-Gaussian laser beam passes through a magnetized plasma. We can say that the relative self-focus of the scattered beam decreases a lot when the laser beam is close to the ideal Gaussian shape. In addition, the focus length becomes shorter because the scattered energy is proportionally reduced. When q, plasma density and magnetic field increase, the fluctuations in the SRS also increase and improve. The reflectivity of SRS is also affected by increasing the q value, plasma density, and magnetic field, as it decreases as these parameters increase.

References

[1] H.A. Salih, V.K. Tripathi and M. Rafat, "Stimulated Raman scattering of the beat wave of counter-propagating lasers", *Phys. Plasmas*, 11(2) (2004) 747-750

[2] V. Sajal and V.K. Tripathi, "Stimulated Raman scattering of a laser beam in a plasma with azimuthal magnetic field", *Phys. Plasmas,* 11(9) (2004) 4206-4212.

[3] H.A. Salih et al., "Stimulated Raman scattering of relativistic laser beam in plasmas", *Phys. Plasmas*, 12(4) (2005) 042302.

[4] K.I. Hassoon, H.A. Salih and V.K. Tripathi, "Stimulated Raman forward scattering of a laser in a plasma with transverse magnetic field", *Physica Scripta*, 80(6) (2009) 065501.

[5] V. Sajal, D. Dahiya and V. K.Tripathi, "Stimulated forward Raman scattering of a laser in a magnetized plasma", *Phys. Plasmas*, 14(3) (2007) 032109.

[6] V. Sajal et al., "Stimulated Raman backward scattering of a laser beam in a magnetized plasma", *Opt. Commun.*, 285(16) (2012) 3563-3566.

[7] E. Woodbury and W. Ng, "Ruby laser operation in the near IR", *Proc. IRE*, 50(11) (1962) 2347-2348.

[8] J.C. White, "Stimulated raman scattering," *Topics Appl. Phys, Tunable lasers*, (2005) 115-207.

[9] F. Palombo and D. Fioretto, "Brillouin light scattering: applications in biomedical sciences", *Chem. Rev.*, 119(13) (2019) 7833-7847.

[10] N. Gupta, S. Kumar and S. Bhardwaj, "Stimulated Raman scattering of self-focused elliptical q-Gaussian laser beam in plasma with axial density ramp: effect of ponderomotive force", *J. Opt.*, 51(4) (2022) 819-833.

[11] D. Biskamp and H. Welter, "Stimulated Raman scattering from plasmas irradiated by normally and obliquely incident laser light", *Phys. Rev. Lett.*, 34(6) (1975) 312.

[12] D. Polli et al., "Broadband coherent Raman scattering microscopy", *Laser Photon. Rev.*, 12(9) (2018) 1800020.

[13] T. Ito, Y. Obara and K. Misawa, "Single-beam phase-modulated stimulated Raman scattering microscopy with spectrally focused detection", *J. Opt. Soc. Amer. B*, 34(5) (2017) 1004-1015.

[14] L. Torrisi et al., "Self-focusing effect in Au-target induced by high power pulsed laser at PALS", *Laser Part. Beams*, 26(3) (2008) 379-387.

[15] A.A. Andreev et al., "X-ray spectroscopy observation of fast ions generation in plasma produced by short low-contrast laser pulse irradiation of solid targets", *Laser Part. Beams*, 25(2) (2007) 267-275.

[16] J. Kline et al., "Investigation of stimulated Raman scattering using a short-pulse diffraction limited laser beam near the instability threshold", *Laser Part. Beams*, 27(438) (2009) 185-190.

[17] S.K.K. Sivamalini et al., "Stimulated Raman scattering in inertial confinement fusion-A review", *AIP Conf. Proc.*, 2800(1) (2023) 020285.

[18] L. Baiwen, "The Complexities on Ultra-Intense Laser Interaction with Plasmas", (2004).

[19] R.J. Focia, "Investigation and characterization of single hot spot laser-plasma interactions", PhD thesis, Massachusetts Institute of Technology (2001).

[20] H.H. Ma et al., "Simulations of laser plasma instabilities using a particle-mesh method", *Plasma Phys. Control. Fusion*, 63(9) (2021) 095005.

[21] R.K. Singh and R. Sharma, "Stimulated Raman backscattering of filamented hollow Gaussian beams", *Laser Part. Beams*, 31(3) (2013) 387-394.

[22] N. Gupta, S. Kumar and S.B. Bhardwaj, "Effect of Self Focusing on Stimulated Raman Scattering of Elliptical q-Gaussian Laser Beam in Underdense Plasma with Axial Density Ramp", *Nonl. Opt. Quant. Opt.*, 58 (2023) 99-126.

[23] K. Walia and T. Singh, "The Influence of self-focused laser beam on Stimulated Raman Scattering process in Collisional Plasma", *Commun. Theor. Phys.*, 75(12) (2023) 1572-9494.

[24] A.S. Ahmed et al., "Stimulated Raman Scattering of Q-Gaussian Laser Beam in an Unmagnetized Plasma", *J. Appl. Sci. Nanotech.*, 3(4) (2023) 10-19.

[25] A.S. Ahmed, H.A. Salih and K.I. Hassoon, "Relativistic Self-Focusing of a q-Gaussian Laser Beam in Plasma by the Influence of Magnetic Field", *Brazilian J. Phys.*, 53(4) (2023) 112.

[26] A.S. Ahmed, H.A. Salih and K.I. Hassoon, "q-Gaussian laser beam for second-harmonic generation from unmagnetized plasma", *J. Opt.*, 53 (2024) 1328-1335.

[27] H.A. Salih, K.I. Hassoon and R.A. Khamis, "Investigating some parameters of q-Gaussian laser beam in plasma", *Phys. Plasmas*, 29(2) (2022) 023103.

[28] K.I. Hassoon, A.K. Sharma and R.A. Khamis, "Relativistic laser self-focusing in a plasma with transverse magnetic field", *Physica Scripta*, 81(2) (2010) 025505.