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Trivelpiece-Gould Mode Excitation in Magnetized Plasmas: A Review of Electron, Ion, Relativistic Beam, and Streaming Ion Effects

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Abstract: This review explores the excitation of Trivelpiece–Gould (TG) modes in bounded magnetized plasmas under different streaming particle beams, such as electron beams and ion beams, as well as relativistic electron streams. The TG mode, an electrostatic wave trapped in cylindrical geometries with an axial magnetic field, is strongly affected by beam–plasma interactions and boundary conditions. Evidence indicates that electron beams, especially those aligned along the magnetic field direction, are capable of driving TG mode instabilities effectively with growth rates highly dependent on beam velocity, density, and anisotropy of temperature. Contrarily, ion beams—more so in low-temperature dusty plasmas—may excite TG modes by resonance with the modified plasma eigen frequencies, as demonstrated in recent analytical and simulation works. The addition of relativistic electron beams results in increased coupling and more extended instability regimes from relativistic mass effects and longitudinal electric field interactions. The presence of dust grains also changes the dispersion and increases low-frequency modes, making the instability richer. These results have been validated by experimental and theoretical research which obtains dispersion relations, calculates growth rates, and investigates mode structures by employing Bessel function eigenmodes in radially confined plasmas. Overall, particle streaming excitation of TG modes presents new opportunities for manipulating plasma wave phenomena in laboratory and space plasmas.
Keywords: Trivelpiece–Gould modes, Beam–plasma interaction, Cold Plasma, Hot Plasma, Dusty plasma, Magnetized plasma, Relativistic electron beams

I. INTRODUCTION

The Trivelpiece–Gould (TG) mode is an electrostatic wave that travels in a magnetized, bounded plasma—most often in a cylindrical shape—and is differentiated by its distinctive dispersion owing to both axial magnetic containment and boundary-induced effects [1]. In contrast to free-space Langmuir waves, TG modes are only found in conducting-boundary plasmas and have discrete radial mode structures owing to the boundary conditions placed on the potential. These modes are particularly characteristic in laboratory plasma columns where the plasma–wall interface exerts a strong influence on wave propagation.

A. In Cold Plasma

In cold plasma—where thermal particle motion can be neglected relative to the phase velocity of the wave—the analysis of TG modes can be simplified, so that more manageable solutions are obtainable with linearized fluid models. In these circumstances, the TG mode has a hybrid nature, being both longitudinal (electrostatic) and transverse (magnetostatic) in nature and having strong coupling between axial and radial electric fields [2], [3]. These modes are also confined below the electron plasma frequency and are strongly dispersive, which makes them valuable diagnostic and model probes for devices of low-temperature plasma [4].

Classically, TG waves were first brought forth by Trivelpiece and Gould in 1959 to account for the dynamics of electrostatic oscillations in a cylindrical plasma surrounded by a static magnetic field [1]. Subsequently, various research studies have broadened the knowledge of TG waves in cold plasma both using fluid and kinetic theories [5], [6]. Theoretical models have predicted that the existence of a magnetic field creates a cut-off at the upper hybrid frequency, and the bounded geometry gives rise to a set of radial eigenmodes governed by Bessel functions [7]. Cold plasma TG modes have been extensively investigated in relation to wave–particle interaction, anomalous transport, and microwave coupling into plasma devices [8]. In experiments with Q-machine plasmas and helicon sources, in particular, clear excitation of these modes in cold plasma situations has been observed, routinely confirming analytical dispersion relations [9], [10]. The TG waves are also involved in mode conversion, parametric instabilities, and sheath-driven effects in bounded plasmas [11], [12].

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This review gives an overview of TG modes in cold, magnetized plasmas. Here, provided an overview of the theoretical basis, dispersion properties, and experimental confirmation, highlighting the influence of geometry, boundary conditions, and magnetic field strength on wave dynamics.

B. Hot plasma

The research of TG waves in hot plasmas, where the phase velocity of the wave is on the order of the thermal particle velocities, brings with it significant kinetic effects like Landau damping, FLR corrections, and resonance wave–particle phenomena. Unlike in cold plasma, where fluid descriptions are adequate, TG modes in hot plasma need a kinetic approach using the Vlasov–Poisson or Vlasov–Maxwell model [13, 14].

In collisionless, hot plasmas, the longitudinal electric field of TG modes can resonate with particles that are traveling along the magnetic field, resulting in Landau damping of the wave [15]. Damping is a function of the electron and ion distribution function and thus renders the mode temperature anisotropy and non-Maxwellian sensitive. Theoretical studies by Laing and Boyd [16] and subsequently by Ichimaru [17] demonstrated that thermal effects cause the broadening and shifting of the dispersion relation of the TG wave.

TG modes in hot plasma also have altered dispersion due to FLR effects when the ion and electron gyro-radii are non-zero. These corrections become important when considering high-frequency TG modes or plasmas with large perpendicular temperature gradients. FLR corrections have been added to kinetic as well as gyrokinetic models to consider the finite temperature effects in magnetized plasma columns [18].

Numerical solutions of the linearized Vlasov equation have been extensively applied to investigate TG wave propagation in hot plasma. Kinetic simulations by Singh and Tripathi [19] demonstrated how increased plasma temperature decreases the growth rate of beam-excited TG instabilities because of increased thermal spread. The same implications were obtained in Refs. [20] and [21], where numerical dispersion analysis verified the stabilization of some TG modes for higher temperatures.

Experimental studies of TG waves in hot plasmas are usually conducted in Q-machines, mirror machines, and linear plasma devices, whose electron temperatures are on the order of several eV. Experiments by Hatakeyama et al. [22] have shown temperature-dependent behavior of wave propagation and attenuation length, justifying kinetic models for hot plasma TG waves.

Furthermore, TG modes in hot plasmas have also been investigated in relation to beam–plasma instabilities and wave-induced transport. When an electron beam is injected parallel to the magnetic field, it can drive TG modes if its velocity is equal to the wave phase velocity, causing resonant energy transfer. But in hot plasmas, this excitation is heavily influenced by thermal smearing of the beam and bulk electron populations [23].

In total, TG modes in hot plasma show complex behavior governed by kinetic damping, thermal dispersion, and nonlinear wave–particle interactions. These phenomena are important in controlled fusion devices, magnetic mirror traps, and space plasmas, where plasma temperatures tend to be high and boundaries are involved in wave reflection and confinement.

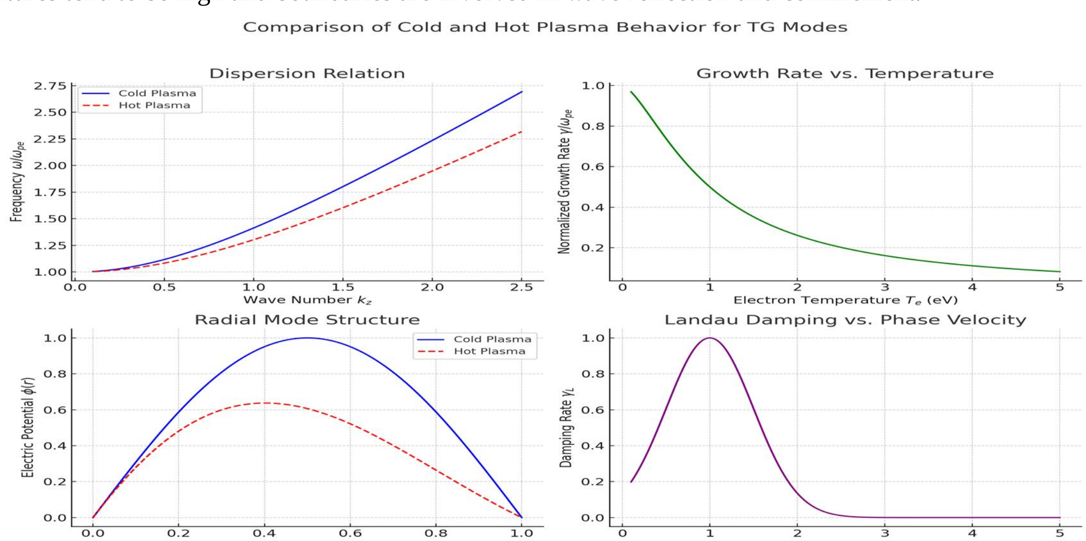

Figure 1:Theoretical trends of TG mode behavior in cold and hot plasmas, based on principles discussed in [1,3,24-26].

C. TG Mode in Dusty Plasmas

Dusty plasma, or also known as complex plasma, is a four-component plasma system that includes electrons, ions, neutral gas, and charged dust grains. The highly charged dust grains, by collecting electrons or ions, have a very marked impact on the behavior of plasma by altering the quasi-neutrality condition and adding new low-frequency wave modes like dust-acoustic waves (DAWs) and dust-ion-acoustic waves. Dusty plasmas occur in many astrophysical settings (such as comet tails and planetary rings) and also in laboratory and industrial plasma devices. Theoretical analysis and experimental observations revealed that the large dust grains serve as inertia carriers, facilitating the propagation of ultra-low-frequency modes and modifying high-frequency wave dynamics as well. Trivelpiece–Gould (TG) modes are electrostatic surface waves found generally in bounded magnetized plasmas. In dusty plasmas, the fact that charged dust grains are present adds more complexity by altering plasma dispersion properties and collective behavior. When an electron beam is injected into such a plasma, it will excite TG modes through resonant wave–particle interactions with the growing consequences of beam-driven instabilities. The altered inertia from the heavy, negatively charged dust and the modified dielectric response of the medium yield new regimes for TG wave propagation. The dust grains decrease the total plasma frequency, and based on dust density and charge, can modify the resonance condition for beam–wave coupling. This renders dusty plasmas a rich regime for exploring modified TG mode dispersion and instability mechanisms, particularly in the presence of beam excitation and external magnetic fields.

II. TG MODE EXCITATION BY ELECTRON BEAM IN DUSTY PLASMAS

Electron beam excitation of Trivelpiece–Gould (TG) modes in dusty plasmas creates rich dynamics different from those found in standard electron–ion systems. TG modes are confined, electrostatic waves present in magnetized plasma columns that respond extremely sensitively to boundary conditions, electron temperature, and external magnetic fields. When an electron beam travels through such a plasma, it gets able to resonate with such electrostatic modes and cause beam–plasma instabilities. The presence of charged dust modifies this interaction by providing other degrees of freedom, i.e., dust charge fluctuations, inertia, and reduction in the plasma frequency. These dust effects impact the dispersion characteristics and can either support or inhibit growth of the beam-excited TG instability, depending on the beam energy, dust density, and grain charge polarity [27–29].

New research has shown that dusty plasmas considerably change the threshold and growth rate of TG mode excitation. For example, Prakash et al. [28] have seen that an increase in the size or density of dust grains in a magnetized cylindrical plasma can enhance the beam-driven instability. In contrast, theoretical models provided by Vladimirov and Nambu [30] and Shukla and Mamun [31] show that dust grains are capable of being energy sinks as well as mediators of extra branches of instability. These results are applicable not only to laboratory experiments with dusty plasmas but also to naturally arising environments like cometary tails, planetary ring plasmas, and the interstellar medium, where electron streams engage with background populations of dusty plasmas. The alteration of TG mode behavior as a function of the presence of dust is a central topic of plasma wave research and has important consequences for plasma confinement, diagnostics, and wave-particle energy transfer processes in advanced plasma systems.

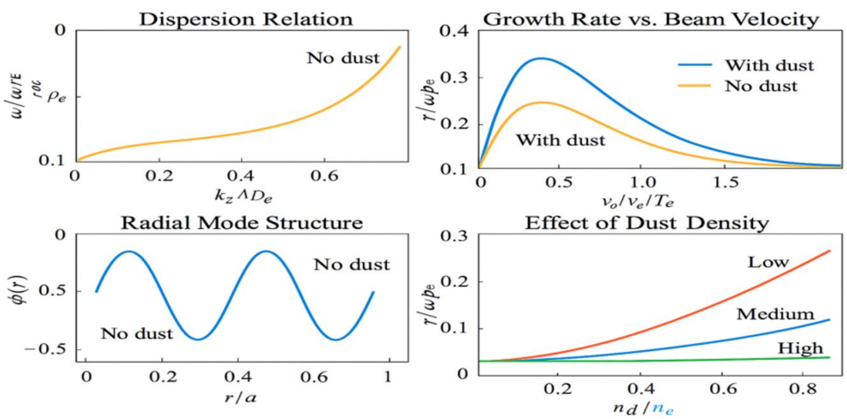

Figure 2: Characteristics of Trivelpiece–Gould (TG) modes in dusty plasmas excited by an electron beam: (a) Dispersion relation showing frequency variation with axial wave number; (b) Growth rate as a function of normalized beam velocity for dusty and dust-free cases; (c) Radial mode structure for the fundamental TG mode; (d) Dependence of instability growth rate on dust density showing low, medium, and high dust scenarios.[34]

III. EXCITATION OF TRIVELPIECE–GOULD MODES BY RELATIVISTIC ELECTRON BEAMS IN DUSTY AND MAGNETIZED PLASMAS

The coupling of relativistic electron beams (REBs) with magnetized plasmas has been a productive subject of investigation owing to its application in laboratory plasma devices and astrophysical environments. In previous foundational research, Sharma and Gahlot [37] investigated the excitation of upper-hybrid and TG modes of magnetized dusty plasmas, highlighting how relativistic gyro-motion of the beam effectively couples with bounded plasma modes. Prakash and Sharma [38] generalized this to the excitation of surface and lower-hybrid waves in a cylindrical dusty plasma geometry, describing the dominant role of beam velocity and magnetic field intensity in determining the TG mode dispersion. Stenzel and Urrutia [39] provided experimental evidence by examining the excitation and propagation of TG waves in uniform plasmas, demonstrating that beam-driven perturbations can match TG mode frequencies and create localized electrostatic fields. Bera et al. [40] conducted numerical simulations illustrating how relativistic beam injection in cold plasmas can excite strong longitudinal oscillations that are similar to TG-like modes, leading to wave breaking in nonlinear regimes.

More recent work has extended these studies into more complex dusty plasma structures under relativistic conditions. Kaur et al. [41] theoretically modeled the excitation of TG modes in cylindrical dusty plasmas by high-energy electron beams and found that higher dust density increases the real frequency and growth rate of the instability, whereas high relativistic beam velocities have a tendency to quench mode excitation due to less phase-space overlap. Sarkar et al. [42] studied nonlinear saturation of beam–plasma instabilities in relativistic conditions and demonstrated that mode structure and energy transfer efficiency are critically dependent on plasma parameters and beam energy. H. Bera and Sengupta [43] studied wakefield generation in cylindrical dusty plasmas and observed that the TG mode may be buried within more general wake structures when short REB pulses excite them. Roy et al. [44] presented nonlinear beam-driven wave structures in confined dusty plasma systems, showing that dust characteristics and relativistic effects can generate complicated wave-packet dynamics, such as mode coupling and soliton-like behaviors. These works cumulatively emphasize the developing knowledge regarding TG mode excitation under conditions of high-energy beam and draw attention to plasma geometry, magnetic confinement, and dust parameters' effects on such modes' dispersion and stability.

IV. EXCITATION OF TRIVELPIECE–GOULD MODES BY ION BEAMS AND STREAMING IONS IN MAGNETIZED PLASMAS

Excitation of Trivelpiece–Gould (TG) modes by high-energy ion beams in magnetized plasma cylinders has gained increased interest because of its applicability in controlled laboratory experiments, fusion devices, and space plasma phenomena. In contrast to electron beams, ion beams interact with the plasma on lower frequencies owing to their larger mass and produce strong electrostatic wave excitations driven by ion cyclotron and lower hybrid dynamics, where TG modes are among the dominant resonant modes in such regimes.

Initial research by Sharma and Sugawa investigated the effect of dust charge fluctuation on ion cyclotron wave instability in plasma cylinders with ion beams. They observed that TG-like electrostatic oscillations can be driven under particular resonance conditions in which the beam velocity is equal to the phase velocity of the TG mode [27]. Then, Prakash et al. studied the effect of dust grain charge and mass on ion beam–driven TG mode excitation in a magnetized dusty plasma. Their analysis demonstrated that the increase of dust density made the mode frequency shift upwards and decreased the instability threshold of the ion beam by causing increased beam–plasma coupling [28].

In a more recent study, Saini and Tripathi theoretically investigated the influence of oblique magnetic fields on the growth of electrostatic TG-like modes driven by ion beams in warm plasma cylinders. Their findings demonstrated that temperature and obliqueness cause asymmetric mode profiles and mode frequency splitting, which can be controlled by changing beam energy or dust parameters [45]. Kumar and Mishra employed fluid modeling to investigate low-frequency TG mode excitation by a streaming ion beam in a collisional, magnetized dusty plasma. Their findings emphasized the ways in which beam density, beam drift velocity, and dust charge polarity may regulate growth rate and cut-off conditions of the TG mode instability [46].

Collectively, these studies illustrate that excitation of the TG mode by ion beams is extremely sensitive to plasma composition (e.g., dust presence), beam parameters, and magnetic field arrangement. Although growth rates tend to be lower than those in electron-beam excitation because of smaller current densities, ion beam–driven TG instabilities have the feature of highly coupled ion cyclotron and hybrid resonance modes, which result in rich dispersion characteristics and potential for mode conversion at nonlinear regimes. This research line has useful implications for plasma stability control in ion thrusters, beam transport systems, and plasma device diagnostic wave excitation.

In the present work, Kaur et al.[47] study the electron particle streaming induced excitation of the Gould–Trivelpiece (TG) mode in a magnetized cylindrical dusty plasma and discuss how the properties of the excited mode are affected by the important plasma parameters. The plasma under consideration consists of electrons, ions, and negatively charged dust grains, while an externally applied static magnetic field is along the cylinder's axis. The authors obtain the linear dispersion relation of the system by employing fluid equations and Poisson's equation, accounting for the cylindrical boundary conditions and using Bessel function formalism to describe the radial eigenmodes. A relativistic analysis of the beam is also employed, involving the inclusion of the Lorentz factor in order to account for high beam velocities. The TG mode, an electrostatic oscillation usually trapped in radial geometry under conditions of magnetization, is demonstrated to be unstable by the presence of a high-energy electron beam, which acts as the driving energy source for the mode excitation.

Detailed parametric analysis of how the dust density, beam energy, magnetic field strength, and plasma density influence both the frequency and growth rate of the TG mode is given in the study. Major conclusions reveal that a rise in the dust number density causes a dramatic boost in the real frequency of the TG mode along with an increased growth rate—implying that the presence of the dust plays an imperative role in beam–plasma coupling and mode development. Conversely, the relativistic character of the streaming particles gives rise to a saturation effect where very high beam energies (higher Lorentz factors) diminish the strength of coupling through phase mismatch with the wave. The findings are presented graphically by means of plots of normalized frequency and growth rate as functions of parameters like beam velocity and dust density. This work stands out as one of the first to provide a detailed treatment of TG mode stability under the combined effects of relativistic streaming particles and dusty plasma, and thus is applicable for laboratory beam-plasma devices and space plasmas with coexisting dust and high-energy particles.

V. CONCLUSION

This review emphasizes the rich and multiscale character of Trivelpiece–Gould (TG) mode excitation in magnetized plasmas exposed to different kinds of streaming particle beams, such as electron beams, ion beams, and relativistic electron streams. The TG mode, as an electrostatic surface-confined wave, is highly responsive to plasma conditions, beam parameters, and magnetic field geometries. The addition of charged dust grains adds further complexity by altering dispersion properties, introducing novel instability thresholds, and modifying wave–particle resonance mechanisms.

Electron beams are still very efficient in exciting TG mode instabilities, particularly under aligned fields, with growth rates depending significantly on the beam energy, density, and anisotropy in temperature. Ion beams, although generally characterized by lower growth instability because of higher mass, have peculiar coupling characteristics close to ion cyclotron and hybrid resonance domains. Relativistic electron beams add more relativistic effects that transform the coupling conditions and impact the nonlinear development of the modes.

Dusty plasmas introduce an additional richness of tunability by frequency shifting modes and facilitating or inhibiting instabilities based on the properties of the dust. Dust density, charge sign, and grain size are critical parameters in altering the dielectric medium and plasma inertia.

Together, the excitation of TG modes in beam-driven magnetized plasmas offers an important diagnostic and control tool for exploring and manipulating wave properties in laboratory and natural plasma systems. Further investigation in this research area is critical to the continued development of applications in plasma confinement, particle acceleration, wave diagnostics, and the study of space and astrophysical plasma processes.

VI. FUTURE PERESPECTIVES

Trivelpiece–Gould (TG) mode excitation in magnetized plasmas remains an exciting area of investigation that provides fruitful avenues for both theoretical development and application. There are several areas for future research to be guided by:

1) Nonlinear and Kinetic Regimes: Whereas the majority of the current work is based on linear theory and fluid models, investigating TG mode behavior in the nonlinear and fully kinetic cases can yield greater insight into mode saturation, energy transfer, and wave-particle trapping processes.
2) Multi-Beam and Multi-Species Effects: Including the dynamics of multiple beam populations (e.g., co-streaming or counter-streaming beams) and blended ion compositions can result in intricate interaction regimes, mode coupling, and possibly new instability branches. 3 Oblique and Inhomogeneous Magnetic Fields: The effects of non-uniform or obliquely incident magnetic fields on TG mode structure and stability are not well studied. These configurations are particularly important for real plasma devices and space plasmas.

3) Advanced Numerical Simulations: The application of high-resolution particle-in-cell (PIC) simulations and hybrid models can be used to visualize the TG mode excitation and evolution in realistic 3D geometries, with increased fidelity capturing dust dynamics, sheath effects, and beam injection mechanisms.
4) Experimental Validation: Laboratory-scale experiments with better diagnostics and control over beam parameters and dust loading can assist in validating theoretical predictions and revealing new physical effects, particularly in bounded and cylindrical plasma configurations.
5) Applications to Space and Astrophysical Plasmas: Future research can concentrate on simulating TG-like modes in naturally occurring dusty and magnetized plasmas like comet tails, planetary rings, and the interstellar medium where streaming particles are interacting with inhomogeneous dusty plasma.
6) Technological Integration: TG mode control and manipulation would be applicable in plasma-based accelerators, ion thrusters, wave-based plasma heating, and diagnostics in fusion devices.

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