

Beam driven plasma instabilities in electron beam ion sources

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Electron beam ion source (EBIS) is capable of generating highly charged ions by ionizing neutral gas atoms using a high-energy electron beam. The generated ions are confined axially and radially by electric and magnetic fields within the breeding region until they are extracted by lowering the axial potential barrier. However, in various EBIS devices, significant ion heating has been observed, which can lead to stagnation in the ionization process, particularly for heavier ions. This stagnation imposes a practical limit on the maximum achievable charge state. To investigate plasma heating in an EBIS, the role of plasma instabilities induced by a Gaussian electron beam in a magnetically confined plasma is examined in detail. The resulting growth rates and dispersion relations confirm the formation of instabilities in the EBIS devices, which are dominant in the form of lower hybrid waves and may be responsible for the limited performance of EBIS in terms of generating fully stripped or highly charged ions. The resulting instability frequencies from the theoretical calculations lie close to ion plasma frequency, i.e., in the MHz range.

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I. INTRODUCTION

Low-energy highly charged ions are of utmost importance in various areas of science, such as atomic physics, nuclear physics, fusion, beam-matter interaction, particle physics, and plasma sciences. The formation of these ions may be challenging, and various ion sources have been developed for the production of highly charged ions. Among these sources, the electron beam ion source (EBIS) is particularly promising device for producing ionic charge state distributions that extend to very high charge states, including fully stripped ions. The concept of EBIS was invented by Donets [1] and the first successful operation of EBIS was conducted in 1972. Later, pioneering work on EBIS was carried out by the ORSAY group [2] and by Levine *et al.* [3] at the

Lawrence Berkeley Laboratory. Unlike electron cyclotron resonance ion sources (ECRIS), in which rf-driven perpendicular heating renders the plasma strongly anisotropic in velocity space and can trigger instabilities such as drift waves [4,5], flute, loss-cone, and other microinstabilities, the electron impact ionization in EBIS produces a highly directional, relatively stable, and low-turbulence plasma, making the instabilities less complex, less intense, and less diverse than those in ECRIS. The ion charge is stepwise increased by collisions with a high-energy electron beam from an electron gun. The electron beam is compressed to a high density under the effect of a strong magnetic field, and its interaction with gas results in a plasma. The radial trapping of resulting ions is due to the negative space charge of the electron beam, while the longitudinal trapping is attained by electrostatic barrier potentials applied to the surrounding coaxial drift tubes. Moreover, the formation of higher charge states depends on the trapping conditions and the ionization time. The characteristic time taken by an ion to go from charge state Z to $Z + 1$ is [6]

$$\tau_z = \frac{1}{\sigma_z v_b n_b} = \frac{e}{\sigma_z J_e}, \quad (1)$$

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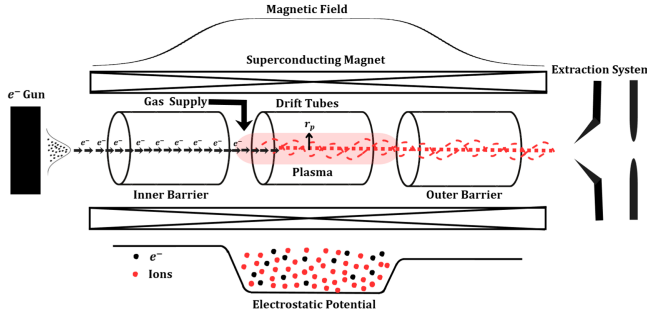


FIG. 1. Schematic diagram of an EBIS device.

where σ_z is the appropriate ionization cross section for the particular charge state, n_b , v_b , J_e , and e are the density of the electron beam, electron beam velocity, beam current density, and electronic charge, respectively. The working principle of an EBIS device along with the magnetic field profile and electrostatic potential trap is shown in Fig. 1.

Although an EBIS, in principle, can form highly charged ions, under certain conditions, the expected charge states are not reached. This is the example of electron beam produced by the MEDeGUN electron gun [7] and launched into TwinEBIS. The high-current beam of >1 A and an energy of around 8 keV is supposed to be compressed to an electron current density of approximately 3200 A/cm^2 in a 2 T solenoid field, over a trapping length of 0.8 m. By injection of CH_4 or C_2H_2 gases, bunches of $>10^8$ fully stripped carbon ions should be produced with a repetition rate exceeding 200 Hz. Extensive tests with natural abundance Ar and isotopically enriched ^{129}Xe have, however, shown that an ion charge corresponding to only a fraction of the available electron space charge can be extracted, as shown in Fig. 2, where the extracted total charge saturates at around 3.8 nC, while the theoretical trapping capacity is 18 nC [8]. In this case, the electron

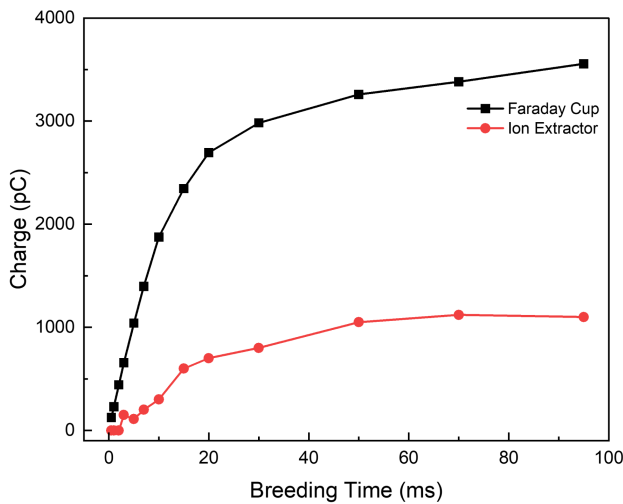
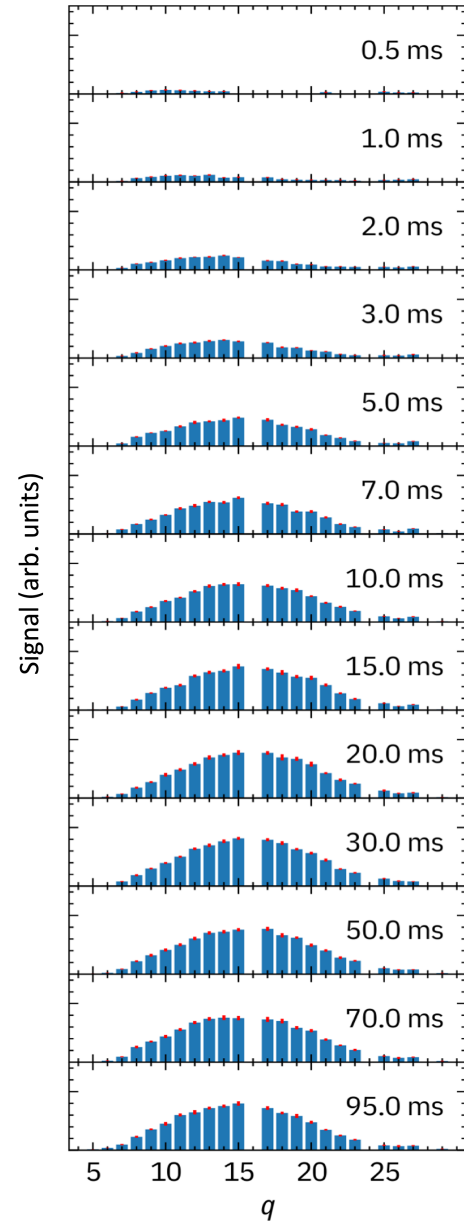


FIG. 2. Plot of the ionic charges measured on a Faraday Cup and the ion extractor electrode as a function of breeding time.

beam current and energy were 1.1 A and 6.7 keV, respectively. For high neutralization cases, ions can be measured on the electron suppressor in front of the collector or at the ion extractor as shown in the plot, but this cannot account for all missing ions, so radial escape inside the breeding region is not ruled out. Furthermore, after approximately 7 ms of breeding, the evolution of charge state distribution to higher charge states is stalled. This is exemplified in Fig. 3, where the corresponding charge state distributions recorded using time of flight (TOF) are displayed. According to first-order simulations that ignore space-charge effects, ion heating and charge exchange, the peak charge state should move, as illustrated in Fig. 4, i.e., from

FIG. 3. Collection of ^{129}Xe charge state spectra as a function of breeding time.

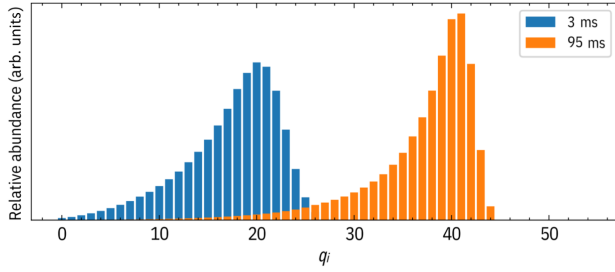


FIG. 4. EBISIM simulation (basic model) [9] of xenon charge breeding, with a fixed current density of 1600 A/cm² and a beam energy of 6.7 keV.

20+ to 41+ when the breeding time is increased from 3 to 95 ms.

The reason behind the limited extracted beam charge and low peak charge states might be the existence of instabilities in the plasma. Plasma instabilities occur when small perturbations in the plasma grow over time, rather than being damped, leading to macroscopic changes, such as turbulence or the generation of new wave modes. Some researchers [10–13] have already worked on the existence of instabilities in an EBIS system. Following the theory of Davidson [14] for the two-stream plasma instability in a non-neutral cylindrical plasma column with constant density immersed in a uniform magnetic field along the axis, Litwin *et al.* [10] found the existence of a convectively unstable electron-ion rotating stream instability in the EBIS. The maximum growth rate of the instability is given by [10]

$$\begin{aligned} \gamma &= \frac{\sqrt{3}}{2} \left[\frac{\omega_{pe}^2 \omega_{pi}^2}{2(\omega_{pe}^2 + \omega_{pi}^2)^{1/2}} \right]^{1/3} \\ &= 5.6 \times 10^{-2} \left[f \varphi \frac{q}{A} \right]^{1/3} \omega_{pe} \\ &= 1.8 \times 10^8 \left[f \varphi \frac{q}{A} \right]^{1/3} \frac{J_e^{1/2}}{E_e^{1/4}}, \end{aligned} \quad (2)$$

where, ω_{pe}/ω_{pi} are the electron/ion plasma frequency, f is the beam neutralization factor, φ is the ion-electron beam overlap factor, q is the ionic charge, A is the ion mass number, J_e is the beam current density, and E_e the electron energy. Later, Krafft and Mark [15] included the effect of longitudinal velocity spread in the electron beam and found no significant difference in the growth rates of unstable modes. The instability may grow to significant size before the ions are extracted or eventually stabilize.

In 1985, Levine *et al.* [11] performed some experiments at the Lawrence Berkeley Laboratory EBIS test stand to study the effect of instabilities on the source performance. The experiments were performed using an x-ray camera, rf spectrum analyzers, and a TOF analyzer. The recorded signal spectrum shows rf noise over a broad frequency range of 1–1000 MHz when the electron beam is on. The recorded

noise intensity and amplitude were found to depend on the operational parameters and a specific range of conditions under which the rf is generated. The emitted electromagnetic signal was taken up by a high-voltage lead, amplified using a 48 dB amplifier and coupled into the spectrum analyzer. Also, the instabilities found by Litwin *et al.* [10] were always unstable, except for a short trap, and the stability criteria require the trap length L to be [13]

$$L < \sqrt{106 \frac{E_e^{3/2}}{[f \varphi \frac{q}{A}]^{2/3} J_e}}. \quad (3)$$

Later, Jacquet and Tagger [12] extended this work to understand the effect of instabilities observed by Litwin *et al.* [10] and Levine *et al.* [11] on the efficiency of ion source. Some additional effects, such as the radial spread of ions due to their finite temperature and electron Landau damping, were taken into consideration. Numerical calculations show that the presence of instabilities leads to ion heating, causing ions to drift beyond the radial extent of the electron beam and thereby significantly reducing the effective current density experienced by the ions. Previous studies stated that the phase velocity of instability is equal to the electron beam velocity, resulting in strong electron Landau damping. However, the numerical calculations suggested no electron Landau damping, even in the cold plasma limit, and the unstable modes were found to have a much larger phase velocity than the electron beam velocity.

Additionally, Hershcovitch [16,17] reviewed the possibility of various types of micro- and macro-instabilities of electron beams in EBIS plasma. Due to high compression of the electron beam by the magnetic field, various plasma instabilities can occur, and also the small size of electron beam makes the kinetic plasma theory inadequate for EBIS devices. He reviewed the possibility of Buneman instabilities, drift waves, electron-ion two-rotating-stream instabilities, diocotron and resonance diocotron instability, and beam-plasma instabilities in EBIS and electron beam ion trap devices. The density gradients resulting from the temperature anisotropy of EBIS plasma provide a favorable environment for the formation of drift waves. Nevertheless, they cannot exist because their frequency is low, i.e., the oscillation time is much greater than the electron beam transit time through the device. Still, there are chances that the steep density gradient may increase their frequency. In addition, the electrons stripped during ionization remain trapped within the device and pose a significant operational challenge. The negative space-charge potential of the electron beam can drive the stripped electrons towards the trap edges, thereby modifying the density gradient in a way that favors the onset of diocotron instability.

In 2016, Shornikov *et al.* [13] analyzed the impact of two-stream instability on an EBIS charge breeder for the TSR@ISOLDE project. The second criterion for the

stability of the EBIS device was pointed out and related to the electron current density as [13]

$$\frac{r_b}{r_D} \approx 1.4 \times \left(\frac{I_e^2}{1.3 \times 10^{-4} \pi r_c^2 J_e \sqrt{E_e}} \right)^{1/2} < 1$$

$$J_e > \frac{1.96 I_e^2}{10^{-4} \pi r_c^2 \sqrt{E_e}}, \quad (4)$$

where, r_b is the electron beam radius, r_D is the Debye screening radius, I_e is the total ion current, and r_c is the cathode radius. By modifying the EBIS design parameters, a narrow working region was found where stable conditions can be met. Furthermore, the reduction of the neutralization factor also provides some relaxation to the length criterion.

II. THEORETICAL METHODOLOGY

Solving the Poisson equation for a defined plasma system is key to obtaining the dispersion relations and growth rates of unstable modes in different plasma systems. Davidson *et al.* [14] studied rigorously this technique and applied it to various kinds of plasma systems. They considered a nonrelativistic, nondiamagnetic, and non-neutral plasma column with cylindrical symmetry under the influence of a uniform longitudinal magnetic field, while the self-generated magnetic fields were neglected during the study. The plasma density profile was considered constant for $r \leq r_p$ and zero beyond r_p up to the conducting wall. The system was assumed to be under the influence of small electrostatic perturbations. Maxwell's equations, momentum balance equations, and continuity equation of plasma were solved to calculate the equilibrium fields and perturbed quantities. Thereafter, solving the Poisson's equation, the dispersion relation and the growth rates of the unstable modes were obtained. Litwin *et al.* [10] utilized this approach for studying EBIS plasmas, and the maximum growth rates for the instabilities as given by Eq. (2).

Later, Sharma and Tripathi [18] developed a theory for calculating frequencies of the unstable modes and their growth rates in plasmas with strong presence of nonlocal effects. The response of plasma species was calculated by solving the fluid equations, while the response of beam particles, which act as a perturbation, was calculated by solving the single-particle equation. They have used this theory extensively for explaining various experiments related to plasma devices, such as formation of lower hybrid waves, upper hybrid waves, ion-cyclotron waves, electron Bernstein waves. Some of the experiments explained by using this theory are listed below: (i) Seiler *et al.* [19] performed experiments using the Princeton Q-1 device and observed a nonresonant perpendicular ion-beam-driven instability just above the cyclotron harmonics near lower hybrid frequency (ω_{LH}). The observed results were in good compliance with the warm-plasma theory. In

cold plasma, the instability frequency was near ω_{pe} . The observed instability frequency mode requires much lesser beam density for destabilization than the parallel ion-beam-driven mode. (ii) Chang *et al.* [20] conducted experiments on the linear plasma device at Bell Telephone Laboratories, where they identified a nonresonant lower hybrid beam-plasma instability. They plotted the unstable wave frequency against beam voltage and the maximum growth rate against beam density and found a strong correlation between their theoretical predictions and experimental results. This study revealed a perpendicular ion-beam-driven lower hybrid mode within a nonisothermal rf discharge plasma, characterized by unmagnetized beam and target ions. Importantly, the instability demonstrated its peak growth rate when phase velocity of the wave along the magnetic field closely matched the thermal velocity of the electrons. (iii) An *et al.* [21] performed studies on the ion-ion lower hybrid waves in the single-ended Iowa Q-machine, which contained K^+ ions, SF_6^- ions, and electrons. The lower hybrid waves were found to move across the magnetic field from the phase measurement studies. The measured frequencies were in accordance with the fluid theory calculations and exhibited an increase in the mode frequency with the negative ion concentrations. (iv) Barkan *et al.* [22] conducted experiments on the formation of electrostatic ion-cyclotron (EIC) waves in the Q-machine. The machine contained a fully ionized ~ 80 cm long and ~ 5 cm diameter potassium plasma under the effect of ≤ 0.4 T magnetic field. Dust consisting of hydrated aluminum silicate particles was introduced into the plasma using a dispenser. The experimental findings justified the previous theoretical prediction that EIC waves are a possible mode of plasma waves and the presence of negatively charged dust grains enhances the growth of this plasma wave mode.

All the experiments listed above have been explained theoretically by various groups based on the nonlocal theory, and the calculated results are in good agreement with the experimental findings. Thus, the theory developed by Sharma and Tripathi [18] is a suitable tool to explore the growth of unstable modes and their dispersion relations originating from beam-plasma interactions. We have utilized this nonlocal theory using a more realistic scenario, considering a Gaussian beam with cylindrical symmetry injected into EBIS-type plasma and the following assumptions: (i) A long non-neutral cylindrical plasma column of radius r_p under the influence of uniform static magnetic field $B \parallel \hat{z}$ is considered. (ii) The plasma is initially in equilibrium having a distribution of electrons and ions. (iii) An electron beam having Gaussian distribution traversing the plasma acts as a perturbation, disrupting the plasma equilibrium.

The perturbed electrostatic potential is given by

$$\phi = \phi_0 e^{i(k_z z + l\theta - \omega t)}, \quad (5)$$

where ϕ_0 is the equilibrium potential, $k_z = \frac{2\pi m}{L}$ and L represents the physical length of the system, and m is an integer. The density profile of the Gaussian beam is given by

$$n_b = \frac{N_0}{2\pi r_b^2} e^{-r^2/2r_b^2}, \quad (6)$$

where N_0 is the number of beam electrons per unit axial length and r_b denotes the beam radius. Initially, the electron beam ionizes the neutral gas, and the plasma is formed. As the plasma reaches a stable equilibrium, the further interaction of the electron beam with plasma species acts as a perturbation. The response of the plasma electrons and ions to the perturbations is calculated by solving the equation of motion.

$$\frac{\partial v}{\partial t} + (v \cdot \nabla) v = \frac{e}{m} \left(E + \frac{1}{c} v \times B \right). \quad (7)$$

By following Sharma and Tripathi approach [18], the resulting perturbed electron and ion densities of the plasma are

$$n_{e1} = -\frac{n_{e0} e}{m_e} \left[-\frac{\nabla_{\perp}^2 \phi_1}{\omega^2 - \omega_{ce}^2} + \frac{k_z^2 \phi_1}{\omega^2} \right] \quad (8)$$

and

$$n_{i1} = \sum_i \frac{n_{i0} Z_i e}{m_i} \left[-\frac{\nabla_{\perp}^2 \phi_1}{\omega^2 - \omega_{ci}^2} + \frac{k_z^2 \phi_1}{\omega^2} \right], \quad (9)$$

where n_{e1} and n_{i1} denote the perturbed electron and ion densities, n_{e0} and n_{i0} denotes the equilibrium electron and ion density for different charged ions, and ω_{ce} and ω_{ci} denote the electron and ion cyclotron frequencies, respectively, and Z_i denotes the charge state of ions. The calculated perturbed beam density is given by

$$n_{b1} = \frac{N_0 e^{-r^2/2r_b^2}}{(\bar{\omega} - l\omega_{cb})^2 m_e} \frac{e}{2\pi r_b^2} \left(\frac{l^2}{r^2} + k_z^2 \right) \phi_1, \quad (10)$$

$$\text{and, } \bar{\omega} = \omega - k_z v_{0\parallel},$$

where ω_{cb} is the beam cyclotron frequency ($\omega_{cb} = \frac{v_{\perp}}{r_b}$) and $v_{0\parallel}$ is the longitudinal beam velocity. By substituting the calculated perturbed quantities in the Poisson's equation

$$\nabla^2 \phi = 4\pi (n_{e1} e - n_{i1} Z_i e + n_{b1} e), \quad (11)$$

we obtain

$$\begin{aligned} \nabla_{\perp}^2 \phi_1 - k_z^2 \phi_1 &= \frac{\omega_{pe}^2}{\omega^2 - \omega_{ce}^2} \nabla_{\perp}^2 \phi_1 - \frac{\omega_{pe}^2}{\omega^2} k_z^2 \phi_1 \\ &+ \frac{\omega_{pi}^2}{\omega^2 - \omega_{ci}^2} \nabla_{\perp}^2 \phi_1 - \frac{\omega_{pi}^2}{\omega^2} k_z^2 \phi_1 \\ &+ \frac{\omega_{pb}^2 e^{-r^2/2r_b^2}}{2(\bar{\omega} - l\omega_{cb})^2 m_e} \left(\frac{l^2}{r^2} + k_z^2 \right) \phi_1, \end{aligned} \quad (12)$$

where $\omega_{pe}^2 = \frac{4\pi n_{e0} e^2}{m_e}$, $\omega_{pi}^2 = \sum_i \frac{4\pi n_{i0} Z_i^2 e^2}{m_i}$, and $\omega_{pb}^2 = \frac{4\pi n_{b0} e^2}{m_b}$ with $n_{b0} = \frac{N_0}{\pi r_b^2} \text{ cm}^{-3}$.

$$\begin{aligned} \nabla_{\perp}^2 \phi_1 + p^2 \phi_1 &= \frac{1}{1 - \frac{\omega_{pe}^2}{\omega^2 - \omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2 - \omega_{ci}^2}} \\ &\times \frac{\omega_{pb}^2}{2(\bar{\omega} - l\omega_{cb})^2} e^{-r^2/2r_b^2} \left(\frac{l^2}{r^2} + k_z^2 \right) \phi_1, \end{aligned} \quad (13)$$

where

$$p^2 = \frac{\frac{\omega_{pe}^2}{\omega^2} k_z^2 + \frac{\omega_{pi}^2}{\omega^2} k_z^2 - k_z^2}{1 - \frac{\omega_{pe}^2}{\omega^2 - \omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2 - \omega_{ci}^2}}. \quad (14)$$

In the cylindrical coordinate system, $\nabla_{\perp}^2 = \frac{\partial^2}{\partial r^2} + (1/r) \frac{\partial}{\partial r} - \frac{l^2}{r^2}$. Thus, Eq. (13) can be rewritten as

$$\begin{aligned} \frac{\partial^2 \phi_1}{\partial r^2} + \frac{1}{r} \frac{\partial \phi_1}{\partial r} - \frac{l^2}{r^2} \phi_1 + p^2 \phi_1 \\ = \frac{1}{1 - \frac{\omega_{pe}^2}{\omega^2 - \omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2 - \omega_{ci}^2}} \frac{\omega_{pb}^2}{2(\bar{\omega} - l\omega_{cb})^2} \\ \times e^{-r^2/2r_b^2} \left(\frac{l^2}{r^2} + k_z^2 \right) \phi_1. \end{aligned} \quad (15)$$

In the absence of the beam, i.e., $\omega_{pb} \sim 0$, Eq. (15) takes the form of Bessel equation as follows

$$\frac{\partial^2 \phi_1}{\partial r^2} + \frac{1}{r} \frac{\partial \phi_1}{\partial r} + \left(p^2 - \frac{l^2}{r^2} \right) \phi_1 = 0. \quad (16)$$

The general solution of Eq. (16) is given by

$$\phi_1 = A J_l(p_n r). \quad (17)$$

Considering the boundary conditions that the potential ϕ remains continuous around the plasma boundary, has a finite value at $r = 0$, and vanishes at the plasma boundary, i.e., $\phi_1(r = r_p) = 0$. Thus, Eq. (17) gives

$$J_l(p_n r_p) = 0, \\ p_n = \frac{X_n}{r_p}, \quad n = 1, 2, 3, \dots \quad (18)$$

X_n are the zeros of the Bessel function. In the presence of a beam, the general solution of Eq. (15) takes the form

$$\phi_1 = \sum_n A_n J_l(p_n r), \quad (19)$$

where A_n is the normalization constant, and

$$A_n = \sqrt{\frac{2}{r_p^2} [J_{l+1}^2(p_n r)]}. \quad (20)$$

Multiplying both sides of Eq. (15) by $r J_l(p_n r)$ and integrating in the limits $0 \rightarrow r_p$, we obtain

$$p^2 - p_n^2 = \frac{1}{1 - \frac{\omega_{pe}^2}{\omega^2 - \omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2 - \omega_{ci}^2}} \\ \times \frac{\omega_{pb}^2}{r_p^2 (\bar{\omega} - l\omega_{cb})^2} \frac{\int_0^{r_p} \left(\frac{l^2}{r^2} + k_z^2\right) e^{-r^2/2r_b^2} J_l^2(p_n r) r dr}{J_{l+1}^2(p_n r_p)}. \quad (21)$$

In the limit $\omega < \omega_{ce}$, the Eq. (21) becomes

$$1 - \frac{k_z^2}{\alpha p_n^2} \frac{\omega_{pe}^2}{\omega^2} - \frac{k_z^2}{\alpha p_n^2} \frac{\omega_{pi}^2}{\omega^2} - \frac{\omega_{pi}^2}{\alpha (\omega^2 - \omega_{ci}^2)} \\ = \frac{\omega_{pb}^2}{\alpha r_p^2 p_n^2 (\bar{\omega} - l\omega_{cb})^2} \frac{\int_0^{r_p} \left(\frac{l^2}{r^2} + k_z^2\right) e^{-r^2/2r_b^2} J_l^2(p_n r) r dr}{J_{l+1}^2(p_n r_p)}, \quad (22)$$

where $\alpha = \frac{k_z^2 + p_n^2}{p_n^2} + \frac{\omega_{pe}^2}{\omega_{ce}^2} \approx 1 + \frac{\omega_{pe}^2}{\omega_{ce}^2}$.

On rearrangement, Eq. (22) can be rewritten as

$$\omega^4 - \left(\omega_{ci}^2 + \frac{k_z^2}{\alpha p_n^2} \omega_{pe}^2 + \frac{k_z^2}{\alpha p_n^2} \omega_{pi}^2 + \frac{\omega_{pi}^2}{\alpha} \right) \omega^2 \\ + \frac{k_z^2}{\alpha p_n^2} \omega_{ci}^2 (\omega_{pe}^2 + \omega_{pi}^2) = \frac{\omega_{pb}^2}{\alpha r_p^2 p_n^2 (\bar{\omega} - l\omega_{cb})^2} \\ \times \frac{\int_0^{r_p} \left(\frac{l^2}{r^2} + k_z^2\right) e^{-r^2/2r_b^2} J_l^2(p_n r) r dr}{J_{l+1}^2(p_n r_p)}. \quad (23)$$

From the above Eq. (23), we obtain the dispersion relation as

$$(\omega^2 - \omega_+^2)(\omega^2 - \omega_-^2)(\bar{\omega} - l\omega_{cb})^2 \\ = \frac{\omega_{pb}^2}{\alpha r_p^2 p_n^2} \frac{\int_0^{r_p} \left(\frac{l^2}{r^2} + k_z^2\right) e^{-r^2/2r_b^2} J_l^2(p_n r) r dr}{J_{l+1}^2(p_n r_p)}. \quad (24)$$

In the absence of beam, $\omega_{pb} \sim 0$ and the roots of Eq. (24) become

$$\omega_+^2 = \omega_{ci}^2 + \omega_{LH}^2 \left[\frac{k_z^2 + p_n^2}{p_n^2} + \frac{k_z^2}{p_n^2} \frac{m_i n_{e0}}{m_e n_{i0}} \right] \\ \approx \omega_{ci}^2 + \omega_{LH}^2 \left[1 + \frac{k_z^2}{p_n^2} \frac{m_i n_{e0}}{m_e n_{i0}} \right] \quad (25)$$

and

$$\omega_-^2 = - \frac{\frac{k_z^2}{\alpha p_n^2} \omega_{ci}^2 (\omega_{pe}^2 + \omega_{pi}^2)}{\omega_{ci}^2 + \omega_{LH}^2 \left[\frac{k_z^2 + p_n^2}{p_n^2} + \frac{k_z^2}{p_n^2} \frac{m_i n_{e0}}{m_e n_{i0}} \right]} \\ \approx - \frac{\frac{k_z^2}{\alpha p_n^2} \omega_{ci}^2 (\omega_{pe}^2 + \omega_{pi}^2)}{\omega_{ci}^2 + \omega_{LH}^2 \left[1 + \frac{k_z^2}{p_n^2} \frac{m_i n_{e0}}{m_e n_{i0}} \right]}, \quad (26)$$

where ω_{LH} corresponds to lower hybrid frequency and is given as

$$\omega_{LH}^2 = \frac{\omega_{pi}^2}{1 + \frac{\omega_{pe}^2}{\omega_{ce}^2}}. \quad (27)$$

In the next section, Eq. (23) has been solved numerically for obtaining dispersion relations and growth rates for EBIS case.

In the presence of beam, i.e., $\omega_{pb} \neq 0$, the maximum growth rate of the unstable frequencies can be obtained by considering $\omega = \omega_+ + \delta = l\omega_{cb} + k_z v_{0\parallel} + \delta$, where δ is the small frequency mismatch. Thus, the growth rate comes out to be as follows:

$$\gamma_{\max} = \text{Im } \delta = \frac{\sqrt{3}}{2} \left[\frac{\omega_{pb}^2 \omega_+ (\omega_+^2 - \omega_{ci}^2)}{2 \alpha r_p^2 p_n^2 (\omega_+^2 - \omega_-^2)} \right. \\ \left. \times \frac{\int_0^{r_p} \left(\frac{l^2}{r^2} + k_z^2\right) e^{-r^2/2r_b^2} J_l^2(p_n r) r dr}{J_{l+1}^2(p_n r_p)} \right]^{1/3}. \quad (28)$$

III. RESULTS AND DISCUSSIONS

Instabilities in plasma can manifest themselves either beneficially or detrimentally, depending on the specific system and context in which they arise. In EBIS, a variety of plasma instabilities [10,11,16,17] have been observed, most of which are generally detrimental to the production of highly charged ions. These instabilities disrupt

plasma confinement, leading to particle loss and energy dissipation, which significantly affect the overall performance of the system. The generation of intense, highly charged ions relies on the careful observation of these instabilities to maintain stable and sustained plasma confinement. Instabilities in EBIS plasma arise from complex interactions between charged particles (electrons and ions) and an external electron beam. In particular, phenomena such as wave-particle interactions, Landau damping, and resonance with external drivers like the electron beam are central to understanding instability growth. Here, instabilities often occur due to the presence of electron beam passing through the non-neutral plasma, which sets up conditions for energy exchange between the beam and the plasma waves. When the growth rate of an instability increases with changing parameters, it typically indicates that these energy exchanges are favoring the growth of perturbations. For example, by varying the plasma density, magnetic field strength, or beam energy, instabilities such as electrostatic two-stream instability, lower hybrid drift instability, or ion-acoustic wave instability may be triggered. These instabilities are quantified through their growth rates, which are indicative of how rapidly the instability will amplify under given conditions. An increasing growth rate signifies that the instability is becoming more disruptive, leading to stronger perturbations in the plasma, which, in turn, degrade the ability of the EBIS to confine and strip ions.

In this study, the estimation of growth rates of the instabilities for various operational parameters of EBIS is performed. As these parameters vary, they influence both the frequency and phase velocity of waves within the plasma, impacting the dispersion relation of the system. The dispersion relation is a critical tool in plasma physics, providing insight into the relationship between wave frequency and wave number for various modes in the plasma. A change in plasma parameters, such as density or temperature, directly modifies the dispersion relation, altering the conditions under which instabilities can grow or be damped. For instance, increasing the magnetic field strength modifies the gyrofrequency of charged particles, which, depending on the wave mode, can either enhance or suppress instabilities. Stronger magnetic fields generally improve confinement by suppressing instabilities such as ion-cyclotron waves, but they may also introduce new resonance conditions that could lead to the growth of other instabilities, such as magnetized electron-ion drift waves. Moreover, the ionization state of the plasma also plays a critical role in shaping instability growth. In highly ionized plasmas, the presence of multicharged ions introduces additional coupling between different plasma modes, including ion-acoustic and electrostatic waves, which can enhance wave-particle interactions. As a result, higher charge states can lead to increased instability growth rates, particularly for modes where ion-electron collisions are significant.

TABLE I. EBIS plasma and operational parameters.

Parameters	Values
Plasma density $n_e(\text{cm}^{-3})$	10^{12}
Electron beam density $n_b(\text{cm}^{-3})$	4×10^{10}
Beam energy (keV)	6.7
Magnetic field (T)	2
Trap length (cm)	80
Beam radius (μm)	100

As a practical application, we consider the standard operating parameters of an EBIS system, as given in Table I. By scanning these parameters across their experimentally observed ranges, while keeping others constant, we aim to map out the full spectrum of instabilities that can arise in the EBIS plasma. For example, changes in the beam current density or trap length will directly affect the coupling between different wave modes, influencing the growth rates of lower hybrid waves and ion-cyclotron waves. Additionally, the trap geometry and boundary conditions (For e.g., end-cap potentials) play a crucial role in determining the modes that are excited within the plasma. From a theoretical perspective, controlling the growth of these instabilities is crucial for optimizing the performance of EBIS devices. Practical methods include adjusting the magnetic field strength to suppress detrimental modes, optimizing the beam density to minimize two-stream instabilities, and ensuring sufficient neutralization to reduce the impact of space-charge effects on the plasma dynamics. Thus, the interplay between plasma density, magnetic field strength, neutralization factor, and beam characteristics governs the behavior of instabilities in EBIS. Understanding these dependencies allows for the tuning of operational parameters to achieve stable confinement and maximize the production of highly charged ions.

The plasma ion density is calculated by considering an overall 50% neutralization (f) of the electron beam except when analyzing the effect of beam neutralization on the frequency and growth rates of the unstable modes. The abundance of different charge states of Xe ions was simulated using EBISIM code for breeding time ~ 95 ms, as shown in Fig. 4, ignoring the space-charge effects. Listed below are various parameters of an EBIS device that have been varied in an operational range to analyze their effect on frequency and growth rates of unstable modes:

Plasma radius: To find a general trend depicting the behavior of instability frequency and its growth with plasma radius, a variation of the plasma radius equal to and 10 times that of the beam radius has been assumed. From Figs. 5(a) and 5(b), instability frequency increases while the growth rates decrease with plasma radius. The maximum growth rate occurs for the system having plasma formation equivalent to the beam radius and subsequently decays for higher values.

Axial wave number: This parameter determines the structure of the perturbation along the plasma axis. The normalized frequency (ω/ω_{pi}) is plotted against the wave number (k_z) for different plasma radii (r_p) in Fig. 5(c). The instability frequency grows rapidly with its wave number, which indicates that the triggering zone of instability is highly compact. A similar trend is predicted in growth rates of instability, as shown in Fig. 5(d). In other words, both the instability frequency and growth rate rise sharply with wave number, which indicates that the unstable process is rooted

in a very localized plasma region with strong gradients. The compact triggering zone supplies free energy to short-wavelength modes, making them highly unstable.

Azimuthal mode number: It is a key parameter that governs how the instability frequency depends on the angular structure of the perturbation and determines which modes dominate the plasma dynamics. In Figs. 5(e) and 5(f), the normalized frequency and growth rates are plotted against the azimuthal mode number (l) for different radius of plasma volume, respectively. The instability

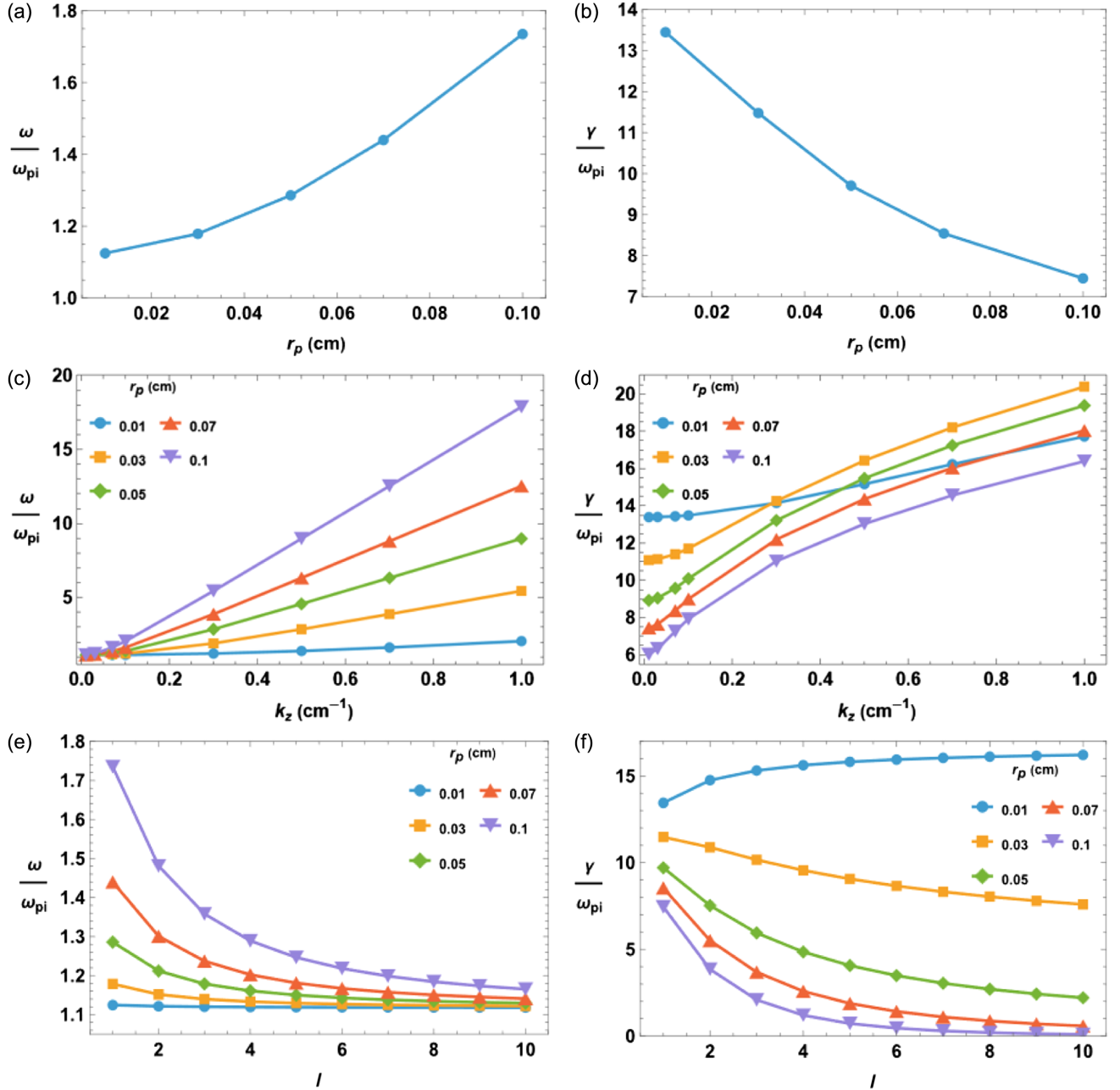


FIG. 5. Behavior of normalized frequency of plasma waves (left) and growth rates [23] of instabilities given by Eq. (28) (right) against radius of the plasma [5(a) and 5(b)], wave number [5(c) and 5(d)], and azimuthal mode number of plasma [5(e) and 5(f)] for the EBIS parameters given in Table I. Only a single parameter is varied in each plot, while the others are kept fixed.

frequency decreases with azimuthal mode number, which indicates diminishing effects of higher order modes. However, more rapid changes are predicted in the growth rates of the plasma instability, except at a plasma radius equivalent to the beam radius (i.e., $r_p = 0.01$ cm), indicating that the onset of instabilities occurs within the electron beam radius and decays radially outward.

Magnetic field: The magnetic field configuration is one of the key parameter of an EBIS device. The solenoid magnet provides the required field strength and also plays

an important role in compressing the electron beam to attain higher beam current densities. The normalized frequency of the unstable waves increases with the magnetic field strength. The growth rates show rise initially, but slightly decay at higher values of magnetic field strength. Thus, having a higher magnetic field favors in general the confinement, but it must be optimized along with other EBIS parameters for formation of highly charged ions as per results in Figs. 6(a) and 6(b).

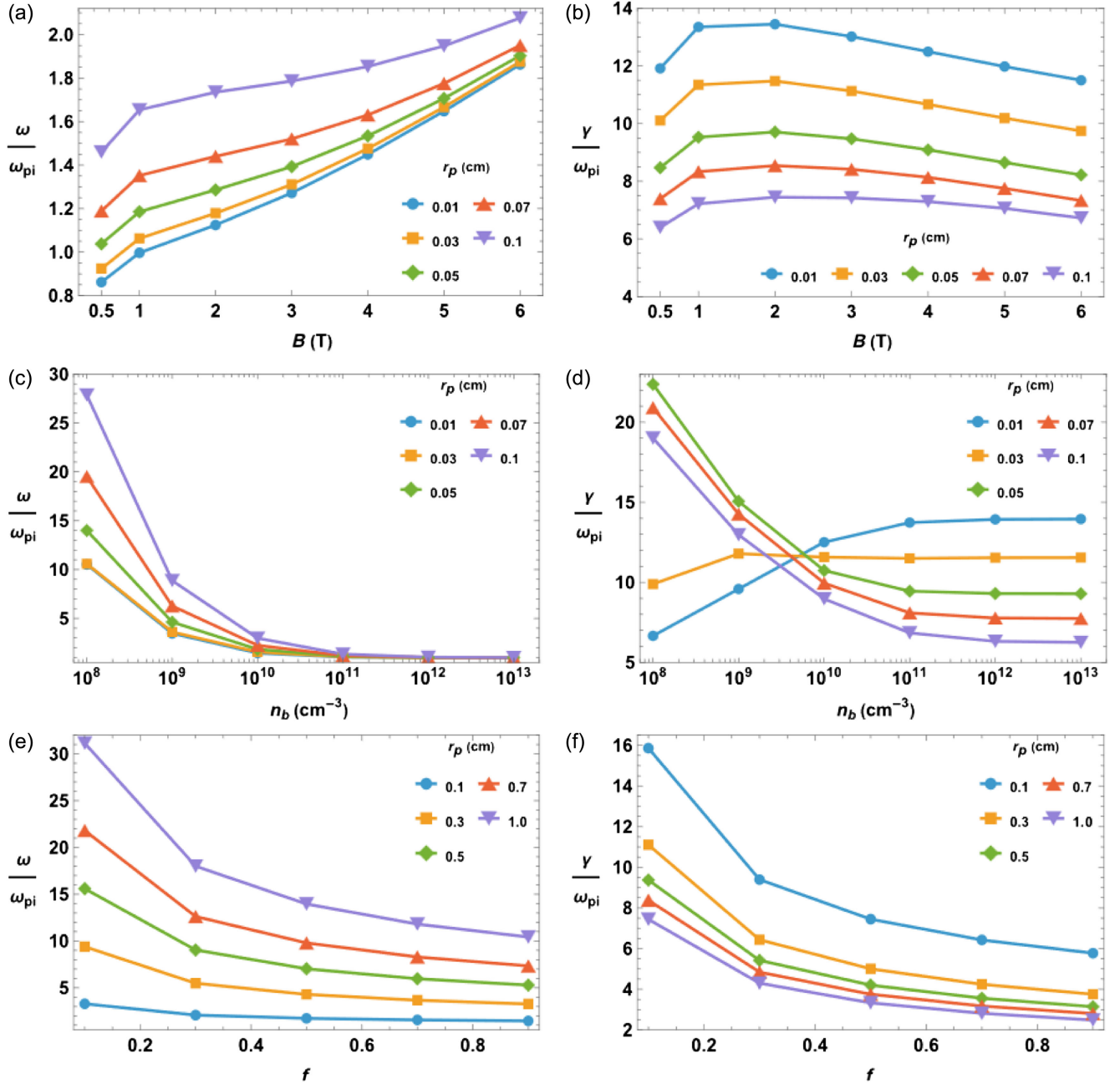


FIG. 6. Behavior of normalized frequency of plasma waves (left) and growth rates [23] of instabilities given by Eq. (28) against magnetic field [6(a) and 6(b)], beam density [6(c) and 6(d)], and beam neutralization [6(e) and 6(f)] for the EBIS parameters given in Table I. Only a single parameter is varied in each plot, while the others are kept fixed.

TABLE II. Maximum growth rates (normalized) of instabilities in TwinEBIS at different plasma radii and for a beam density $4.0 \times 10^{12} \text{ cm}^{-3}$ with 50% neutralization.

$r_p(\text{cm})$	0.01	0.03	0.05	0.07	0.1
γ/ω_{pi}	13.949	11.542	9.290	7.743	6.261

Electron beam density: The electron beam is responsible for the ionization in an EBIS device and drives the formation of higher charge states. A higher density of the electron beam suppresses the frequency of unstable modes and saturates for higher beam densities as shown in Fig. 6(c). The growth rate as shown in Fig. 6(d), also decreases with the increased electron beam density except when the plasma volume radius (r_p) is equal to the beam radius (r_b) of the electron beam and initial slight rise for $r_p = 3 r_b$. Thus, higher beam densities are favorable for attaining higher charge states and lower growth rates of instabilities.

Beam neutralization: It is a measure of the compensation of electron beam's self-field by opposite charges from plasma or background gas, reducing space-charge effects and partially neutralizing the negative charge. In Figs. 6(e) and 6(f), we have plotted the effect of beam neutralization on the frequencies and growth rates of the unstable modes. The instability frequency as well as the growth rates decrease with an increasing rate of beam neutralization, which means achieving better neutralization helps in stabilizing the system.

For the TwinEBIS ion source, the length of the ionization region where plasma is formed is approximately 80 cm, which corresponds to $k_z \approx 0.078 \text{ cm}^{-1}$ and beam densities are of the order of 10^{12} cm^{-3} . The maximum value of the growth rates for different plasma radius are given in Table II. As the plasma volume expands, there is a significant increase in the growth rates of the plasma instabilities.

IV. CONCLUSIONS

The analysis of EBIS plasma focuses on the interaction between a Gaussian electron beam and a non-neutral plasma by solving the continuity and Poisson equations to estimate dispersion relations and instability growth rates. Motivated by the need to obtain higher charge states or fully stripped ions in EBIS, it is essential to carefully examine the onset of plasma instabilities with respect to the system's operational parameters. A delicate balance between electron beam parameters (current density, energy, and profile) and plasma parameters (radius, density, charge state, and ion species) is critical for achieving stable confinement. Compared to traditional methodologies, including the Litwin formula [10], we have derived a modified expression for instability frequencies and growth rates in EBIS under practical approximations. Our approach incorporates the effects of multiple operational parameters,

allowing more accurate predictions. The theoretically calculated instability frequencies lie in a few hundred MHz range for various combinations of the operational parameters of an EBIS device. Also, the rf measurements done by Levine *et al.* [11] at the LBL EBIS test stand reveal that the instability frequencies lie in the MHz range and their existence depends on three variables: electron plasma density, electron beam current, and density of trapped ions. Thus, the theoretical results are in accordance with the experimentally measured results. The instability frequencies and growth rate decrease with azimuthal mode of plasma, electron beam density, and neutralization factor but increase with magnetic field and plasma radius. High magnetic fields might improve plasma confinement, but can also trigger instabilities. The refined estimation of plasma instabilities using this new methodology provides insight into the limitations of EBIS and may contribute to the potential improvements to enhance its overall efficiency. In the future, measurements related to plasma parameters such as electron density, ion density, and plasma radius may be explored at TwinEBIS to establish the proposed theoretical framework. Other measurements related to rf emission and beam current oscillations may also be envisaged to establish a comprehensive comparison between the theory and observations. Understanding these key underlying concepts will help in designing next generation EBIS devices with improved stability and achieving highly charged ions.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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