

**MAGNETIC FIELD EVOLUTION BY WEIBEL  
INSTABILITY IN COUNTER-STREAMING PLASMAS**

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**DEPARTMENT OF PHYSICS  
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**MAGNETIC FIELD EVOLUTION BY WEIBEL  
INSTABILITY IN COUNTER-STREAMING PLASMAS**

**by**

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**Submitted**

**in fulfillment of the requirements of the degree of Doctor of Philosophy**

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*To my family and cherished loved ones,  
&  
to all who have inspired and supported me along the way*

# Certificate

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This is to certify that the thesis titled “**Magnetic Field Evolution by Weibel Instability in Counter-Streaming Plasmas,**” submitted by **Mr. Rakesh Kumar**, is a bonafide record of his original research work conducted under our guidance and supervision. The thesis is deemed worthy of consideration for the degree of Doctor of Philosophy, and the results presented herein have not been submitted, either in part or in full, to any other university or institution for the award of any degree or diploma.

We hereby confirm that he has undertaken the required course of research and endorse the thesis for the award of the Doctor of Philosophy degree.



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**Rakesh Kumar**

## Abstract

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Astrophysicists and laser-plasma researchers have paid considerable attention to the Weibel instability. In plasma physics, the mechanism behind magnetic field generation in different types of plasmas remains an intriguing mystery. In 1959, Weibel introduced this instability as one of a fundamental method for amplifying magnetic fields and initiating self-seeding in plasmas. Astrophysics posits that this process is responsible for generating intense collisionless shocks in various contexts, including  $\gamma$ -ray bursts and associated afterglows, the encounter of relativistic streams, and more. The Weibel instability is frequently cited in cosmic ray production studies as the mechanism capable of generating the intense magnetic fields necessary for scattering charged particles and facilitating their acceleration through the second-order Fermi mechanism.

Both relativistic and non-relativistic plasma jets are commonly observed in astrophysical environments and laboratory plasma systems. When the charged particles with relativistic and non-relativistic velocities transmit through surrounding plasma, which generates a reverse current, plasma instabilities occur both longitudinally and transversely as a result of the interactions between these currents. These instabilities are recognised as potential method in order to the generation of unprompted magnetic fields within violent astrophysical settings, including  $\gamma$ -ray bursts (GRBs), and others, incorporating laboratory plasmas, like inertial confinement.

A variety of facets of waves and instabilities in various plasmas are investigated in this work. We evaluated the monotonically increasing rates instabilities arising from counter-propagating anisotropic plasmas in unmagnetized conditions due to electron-positron counter-streaming, in uniform and nonuniform plasma density. Extensive analytical and computational investigations of plasma instabilities are being conducted to elucidate potential processes for simply increasing magnetic fields. The kinetic theory has been used to accurately comprehend both rapid and gradual processes in plasmas. Particular uses are in  $\gamma$ -ray bursts along with others.

Particle-in-cell (PIC) simulations serve as a robust instrument for investigating astrophysical plasmas, and their application in one-dimensional, two-dimensional, and three-dimensional systems, which have advanced significantly, offering unique insights at different levels of complexity. PIC simulations are a fundamental computational tool used to investigate the kinetic behaviour of astrophysical plasmas. These simulations model plasma dynamics by tracking the motion of charged particles (macro-particles) under self-consistent electromagnetic fields, solving Maxwell's equations and the relativistic moment equation.

Particle-in-cell simulations are being used to analyse how shocks form and propagate in collisionless plasmas, like supernova remnants,  $\gamma$ -ray bursts, and investigates instabilities (e.g., Weibel instability) that generate and amplify magnetic fields in shock regions. Particle-in-cell models demonstrate how these instabilities amplify magnetic fields in collisionless plasmas, crucial for understanding astrophysical jets and interstellar medium interactions. Particle-in-cell simulations are essential in elucidating in unveiling the complex behaviours of astropasmas.

To address some of these issues, this thesis examines various astrophysical and laboratory scenarios involving like counterstreaming plasma flows with a constant external magnetic field parallel to the counterstreaming electron beam within a neutral background, having ions at rest, through a combination of analytical modeling and PIC simulations. There is an emphasis placed on both the linear and nonlinear effects of the external magnetic field.

In the end, we have also explored purely growing modes in unmagnetized plasmas, a comparatively rapidly expanding area within the field of plasma physics. This research could be significant for astrophysical plasmas, such as those found in the solar plasma outflows.

खगोल भौतिकविदों और लेजर-प्लाज्मा शोधकर्ताओं ने वेइबल अस्थिरता (Weibel Instability) पर काफी ध्यान दिया है। प्लाज्मा भौतिकी में, विभिन्न प्रकार के प्लाज्मा में चुंबकीय क्षेत्र के निर्माण के पीछे की प्रक्रिया एक रोमांचक रहस्य बनी हुई है। 1959 में, वेइबल ने इस अस्थिरता को चुंबकीय क्षेत्रों को बढ़ाने और प्लाज्मा में आत्म-बीजारोपण (self-seeding) शुरू करने के लिए एक मूलभूत प्रक्रिया के रूप में प्रस्तुत किया। खगोल भौतिकी का मानना है कि यह प्रक्रिया तीव्र टकराव रहित झटकों (collisionless shocks) को उत्पन्न करने के लिए जिम्मेदार है, जो विभिन्न संदर्भों में देखे जाते हैं, जैसे गामा-किरण विस्फोट ( $\gamma$ -ray bursts) और उनके पश्चप्रकाश (afterglows), सापेक्षिक धारा (relativistic streams) का सामना, और अन्य। वेइबल अस्थिरता को कॉस्मिक किरण उत्पादन के अध्ययन में अक्सर उस प्रक्रिया के रूप में उद्धृत किया जाता है जो आवेशित कणों को फैलाने और उन्हें दूसरे-क्रम के फ़र्मी तंत्र (second-order Fermi mechanism) के माध्यम से त्वरित करने के लिए आवश्यक तीव्र चुंबकीय क्षेत्रों का निर्माण कर सकती है।

सापेक्षिक (relativistic) और गैर-सापेक्षिक (non-relativistic) प्लाज्मा जेट्स अक्सर खगोल भौतिकीय और प्रयोगशाला प्लाज्मा वातावरण में देखे जाते हैं। जब सापेक्षिक और गैर-सापेक्षिक गतियों वाले आवेशित कण आसपास के प्लाज्मा से गुजरते हैं, तो वे एक प्रतिगामी धारा (reverse current) उत्पन्न करते हैं। इन धाराओं के बीच अंतःक्रियाओं के परिणामस्वरूप प्लाज्मा में अनियमितताएँ (plasma instabilities) होती हैं, जो अनुदैर्घ्य (longitudinally) और अनुप्रस्थ (transversely) दोनों रूपों में प्रकट होती हैं। ऐसी अस्थिरताओं को तीव्र खगोल भौतिकीय घटनाओं, जैसे गामा-किरण विस्फोट (GRBs), और प्रयोगशाला प्लाज्मा जैसे जड़त्वीय प्रतिबंधन (inertial confinement) में स्वतःस्फूर्त चुंबकीय क्षेत्रों (spontaneous magnetic fields) के निर्माण के लिए एक संभावित विधि के रूप में पहचाना जाता है।

इस कार्य में विभिन्न प्लाज्मा में तरंगों और अस्थिरताओं के कई पहलुओं की जांच की गई है। हमने समरूप और असमरूप प्लाज्मा घनत्व में, इलेक्ट्रॉन-पॉज़िट्रॉन के विपरीत प्रवाह (counter-streaming) के कारण, बिना चुंबकीय क्षेत्र वाली स्थितियों में विपरीत दिशाओं में प्रवाहित होने वाले अनैसोट्रॉपिक प्लाज्मा से उत्पन्न अस्थिरताओं की दरों का मूल्यांकन किया। चुंबकीय क्षेत्रों को सरलता से बढ़ाने की संभावित प्रक्रियाओं को स्पष्ट करने के लिए प्लाज्मा अस्थिरताओं की व्यापक विश्लेषणात्मक और गणनात्मक जांच की जा रही है। प्लाज्मा में त्वरित और धीमी प्रक्रियाओं को सटीक रूप से समझने के लिए काइनेटिक सिद्धांत (kinetic theory) का उपयोग किया गया है। गामा-किरण विस्फोटों (GRBs) और अन्य घटनाओं में इसका विशेष उपयोग देखा गया है।

पार्टिकल-इन-सेल (Particle-in-Cell, PIC) सिमुलेशन खगोल भौतिकीय प्लाज्मा का अध्ययन करने के लिए एक मजबूत उपकरण के रूप में कार्य करता है, और इसे एक-आयामी, दो-आयामी और तीन-आयामी प्रणालियों में लागू करने में उल्लेखनीय प्रगति हुई है। यह विभिन्न स्तरों पर जटिलताओं को समझने के लिए अनोखी जानकारी प्रदान करता है। PIC सिमुलेशन खगोलीय प्लाज्मा के गतिशील व्यवहार (kinetic behaviour) का अध्ययन करने के लिए एक मौलिक गणनात्मक उपकरण है। ये सिमुलेशन प्लाज्मा की गतिशीलता को मॉडल करते हैं, जिसमें आवेशित कणों (मैक्रो-कणों) की गति का पता लगाया जाता है, जो आत्म-सुसंगत विद्युत-चुंबकीय क्षेत्रों (self-consistent electromagnetic fields) के तहत होती है, और मैक्सवेल समीकरण (Maxwell's equations) और सापेक्षिक क्षण समीकरण (relativistic moment equation) को हल करते हैं।

पार्टिकल-इन-सेल (Particle-in-Cell, PIC) सिमुलेशन का उपयोग यह विश्लेषण करने के लिए किया जा रहा है कि टकराव रहित प्लाज्मा (collisionless plasmas), जैसे सुपरनोवा अवशेष (supernova remnants),  $\gamma$ -किरण विस्फोट ( $\gamma$ -ray bursts), में झटके (shocks) कैसे बनते और

फैलते हैं। साथ ही, यह उन अस्थिरताओं (जैसे, वेइबल अस्थिरता) का अध्ययन करता है जो झटका क्षेत्रों में चुंबकीय क्षेत्रों का निर्माण और प्रवर्धन करती हैं। पार्टिकल-इन-सेल मॉडल यह प्रदर्शित करते हैं कि ये अस्थिरताएँ टकराव रहित प्लाज्मा में चुंबकीय क्षेत्रों को कैसे बढ़ाती हैं, जो खगोल भौतिकीय जेट्स (astrophysical jets) और इंटरस्टेलर माध्यम (interstellar medium) की परस्पर क्रियाओं को समझने के लिए महत्वपूर्ण है। पार्टिकल-इन-सेल सिमुलेशन खगोलीय प्लाज्मा के जटिल व्यवहार को उजागर करने में आवश्यक भूमिका निभाते हैं।

इन समस्याओं को हल करने के लिए, यह शोध प्रबंध (thesis) विभिन्न खगोलीय और प्रयोगशाला परिदृश्यों की जांच करता है, जैसे कि एक स्थिर बाहरी चुंबकीय क्षेत्र के साथ विपरीत प्रवाह वाले प्लाज्मा प्रवाह, जिसमें तटस्थ पृष्ठभूमि में स्थिर आयन और विपरीत प्रवाह करने वाली इलेक्ट्रॉन बीम होती है। विश्लेषणात्मक मॉडलिंग और पार्टिकल-इन-सेल सिमुलेशन के संयोजन के माध्यम से, बाहरी चुंबकीय क्षेत्र के रैखिक (linear) और गैर-रैखिक (nonlinear) प्रभावों पर विशेष जोर दिया गया है।

हमने बिना चुंबकीय क्षेत्र वाले प्लाज्मा (unmagnetized plasmas) में केवल बढ़ते हुए रूपों (purely growing modes) का भी अध्ययन किया है, जो प्लाज्मा भौतिकी के क्षेत्र में तुलनात्मक रूप से तेजी से विकसित हो रहा एक क्षेत्र है। यह शोध खगोलीय प्लाज्मा, जैसे सौर प्लाज्मा प्रवाह (solar plasma outflows) में पाए जाने वाले प्लाज्मा के लिए महत्वपूर्ण हो सकता है।

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**Fig. 3.1:** Growth rate  $\gamma / \omega_p$  as a function of normalized wavenumber  $K_p$  for  $T_y/T_x = 6$  (blue), 4 (red), 2 (yellow).

**Fig. 3.2:** Temporal evolution of the field energies corresponding to  $E_x$ ,  $E_y$  and  $B_z$  for  $\delta n/n_0 = 0.75$  on logarithmic scale (a), and temporal evolution of the transverse magnetic field energy ( $B_z$  - component) corresponding to different plasma density distribution:  $\delta n/n_0 = 0$  (black line),  $\delta n/n_0 = 0.25$  (red line),  $\delta n/n_0 = 0.50$  (blue line),  $\delta n/n_0 = 0.75$  (green line), respectively (b).

**Fig. 3.3:** Temporal profiles of the temperature anisotropy for the case of homogeneous (black) and inhomogeneous density distribution, respectively. The black curve shows the temperature anisotropy for homogeneous distribution (i.e.,  $\delta n/n_0 = 0$ ). The red, green, and brown curve is corresponding to inhomogeneous distribution for  $\delta n/n_0 = 0.25, 0.50, 0.75$  respectively.

**Fig. 3.4:** The process of anisotropy generation in the downstream region. The green dashed circles are isotropic density region in  $P_x P_y$  plane. The solid red circles represent the momentum distribution. The left, middle, and right columns represent the upstream region, region behind the shock and the downstream region, respectively.

**Fig. 3.5:** Temporal evolution of transverse magnetic field component  $B_z$  for the inhomogeneous plasma distribution at two different simulation times: (a) at  $t \sim 8 \omega_{pe}^{-1}$  and (b) at  $t \sim 110 \omega_{pe}^{-1}$ .

**Fig. 3.6:** 2D snapshots of k-spectra of z-component of the magnetic field for the inhomogeneous plasma distribution corresponding to two different times. (a) at  $t \sim 8 \omega_{pe}^{-1}$  and (b) at  $t \sim 110 \omega_{pe}^{-1}$ .

**Fig. 4.1:** (a) Shows the temporal evolution of the energy density of  $E_x$ ,  $E_y$ , and  $B_z$  components on the logarithmic scale for counter-streaming plasma flows. (b) Shows the magnetic energy density for different initial drift velocity.

**Fig. 4.2:** Depicts the time evolution of the magnetic field profile for counter streaming plasma flows with drift velocity  $v_d = 0.6c$  (column first),  $v_d = 0.7c$  (column second) and  $v_d = 0.8c$  (column third). Figs (a), (b), and (c) shows magnetic spatial distribution at simulation time 7, Figs (d), (e), and (f) at simulation time 100, Figs (g), (h), and (i) at simulation time 500, and Fig (j), (k) and (l) shows magnetic spatial distribution at simulation time 1000 respectively.

**Fig. 4.3:** Shows the phase space densities of the distribution function of  $f(y, v_x)$  of beam one in the units of computational particles: column one for  $v_d = 0.6c$  (a) depicts the initial time distribution, (d) at simulation time  $t = 7$ , (g) at simulation time  $t = 100$ , (j) at simulation time  $t = 500$ , at the end (m) simulation time  $t = 1000$ . Similarly, column two for  $v_d = 0.7c$  and column three for  $v_d = 0.8c$  for the same simulation time.

**Fig. 4.4:** Shows the number density distribution at the end of the simulation (a) depicts the number density, (b) x-component of current density for the drift velocity  $v_d = 0.8c$ , (c) depicts the number density and (d) x-component of current density for the drift velocity  $v_d = 0.7c$ , (e) depicts the number density and (f) x-component of current density for the drift velocity  $v_d = 0.6c$ .

**Fig. 5.1:** The schematic representation of the beam plasma system.

**Fig. 5.2:** Shows the z-component of the magnetic field (black line) and the x (red) and y-component (blue) of electric field energies.

**Fig. 5.3:** Spatial fluctuations of the magnetic field at the different simulation times: (a)  $\omega_{pe}t=14$ , (b)  $\omega_{pe}t=50$ , (c)  $\omega_{pe}t=100$ , (d)  $\omega_{pe}t=200$ , (e)  $\omega_{pe}t=400$  at the end of the simulation (f)  $\omega_{pe}t=1000$ .

**Fig. 5.4:** Beam electron phase space  $(x, v_y)$  at (a)  $\omega_{pe}t=14$ , (b)  $\omega_{pe}t=50$ , (c)  $\omega_{pe}t=100$ , (d)  $\omega_{pe}t=200$ , (e)  $\omega_{pe}t=400$  at the end of the simulation (f)  $\omega_{pe}t=1000$ .

**Fig. 5.5:** Phase space  $(x, v_y)$  of background plasma electrons at (a)  $\omega_{pe}t=14$ , (b)  $\omega_{pe}t=50$ , (c)  $\omega_{pe}t=100$ , (d)  $\omega_{pe}t=200$ , (e)  $\omega_{pe}t=400$  at the end of the simulation (f)  $\omega_{pe}t=1000$ .

**Fig. 5.6:** 5.6. Formation of background plasma cavity: The upper Panel shows the density of background plasma electrons (red) and the beam electrons (blue) at simulation time  $t = 400$  and the lower Panel at simulation time  $t = 1000$ .

**Fig. 6.1:** Growth rate of instability versus the electron gyrofrequency  $\omega_{ce}$ .

**Fig. 6.2:** Temporal evolution of the field energy of the z-component of the magnetic field for different values of applied external magnetic field.

**Fig. 6.3:** Shows the phase space densities of the distribution function of  $f(x, v_y)$  of beam one (moving along positive  $\hat{y}$ -direction) in the units of computational particles. All the phase space

distribution are at the end of simulation. Panel (a) depicts the phase space distribution for  $\omega_{ce} = 0.020$ , panel (b) depicts the phase space distribution for  $\omega_{ce} = 0.045$ , and panel (c) depicts the phase space distribution for  $\omega_{ce} = 0.056$ .

**Fig. 6.4:** 6.4. Shows the phase space densities of the distribution function of  $f(x, v_z)$  of beam one (moving along positive  $\hat{y}$ -direction) in the units of computational particles. All the phase space distribution are at the end of simulation. Panel (a) depicts the phase space distribution for  $\omega_{ce} = 0.020$ , panel (b) depicts the phase space distribution for  $\omega_{ce} = 0.045$ , and panel (c) depicts the phase space distribution for  $\omega_{ce} = 0.056$ .

**Fig. 6.5:** The spatial structure of magnetic field for  $\omega_{ce} = 0.020$  at the end of simulation time, i.e.  $t = 1000$ .

**Fig. 6.6:** The left panel shows the spatial profile of the magnetic for  $\omega_{ce} = 0.020$  at the end of simulation time, i.e.  $t = 1000$ . The right panel shows the corresponding total electron density of each beam. Here  $n_1$  represents the electron beam moving along the positive  $y$ -direction and  $n_2$  represents the electron beam moving along the negative  $y$ -direction.

# List of Symbols

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- $A$  : Magnetic vector potential  
 $B$  : Magnetic field  
 $B_o$  : External Magnetic Field  
 $B_1$  : Perturbed magnetic field  
 $\nabla_p$  : Momentum derivative  
 $\nabla P_e$  : Pressure gradient term for electrons  
 $\Delta x$  : Grid spacing along  $x$ -axis  
 $\Delta y$  : Grid spacing along  $y$ -axis  
 $\delta n$  : Fluctuation in number density  
 $E$  : Electric field  
 $\epsilon_0$  : Permittivity of free space  
 $e$  : Electronic charge  
 $f$  : Distribution function  
 $\Gamma$  : Growth rate of the instability  
 $\gamma$  : Relativistic factor  
 $\gamma_p$  : Normalized growth rate  
 $J$  : Current density  
 $K_B$  : Boltzmann constant  
 $K_p$  : Normalized wave number  
 $L$  : Finite plasma size/characteristics length of plasma  
 $L_x$  : Length of the simulation box along the  $x$ -direction  
 $L_y$  : Length of the simulation box along the  $y$ -direction  
 $\lambda_D$  : Debye length  
 $\lambda_B$  : Cavity diameter  
 $m$  : Mass of the particle  
 $m_e$  : Mass of electrons  
 $\mu_0$  : Magnetic permeability of free space  
 $N_x$  : Number of grids along  $x$ -axis  
 $N_y$  : Number of grids along along  $x$ -axis  
 $n(r, t)$  : Number density of plasma particle  
 $n_i$  : Ion density  
 $n_e$  : Electron density  
 $n_0$  : Constant number density

$n_e$  : Electron density  
 $n_{oe}$  : Electron density at equilibrium  
 $n_{1e}$  : Perturbed electron density  
 $n(r, t)$  : Number density of plasma particle  
 $\omega$  : Frequency of Electromagnetic wave  
 $\omega_{ce}$  : Cyclotron frequency  
 $\omega_{pe}$  : Plasma frequency  
 $\mathbf{p}$  : Momentum  
 $q_j$  : Charge of the particle  
 $\mathbf{r}$  : Position vector of plasma particle  
 $\rho$  : Charge density  
 $T_x$  : Temperature along the  $x$ -axis.  
 $T_y$  : Temperature along the  $y$ -axis.  
 $\mathbf{v}_j$  : Velocity of particle  
 $\mathbf{v}_d$  : Drift velocity  
 $\mathbf{v}_{th}$  : Thermal velocity  
 $\mathbf{v}_{oe}$  : Velocity at equilibrium  
 $\mathbf{v}_{1e}$  : Perturbed velocity  
Z: Nucleus charge