Transverse Beam Emittance Growth Due to Low Frequency Instabilities in Microwave Ion Source Plasma

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Outline

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Motivation

- Maintaining the least emittance growth or minimum emittance value throughout the ion beam transport system is essential to avoid any beam losses at the entry and exit of any linear accelerators.
- Initial starting point of emittance growth of ion beam hails from the ion source operating conditions, magnetic field configuration, ion temperature and its plasma instability conditions
- Investigation of beam emittance growth due to different source operating conditions (pressure, power, magnetic field etc.) is studied previously.
- However, influences of plasma instability on the transverse beam emittance growth is still unexplored.
- Beam current oscillations due to plasma drift waves and cyclotron kinetic plasma instabilities is observed.
- Although multiple close frequency heating (MCFH) in microwave ion source is proved to a quite promising tool in mitigating kinetic plasma instabilities, the impacts of MCFH on beam emittance growth is still unknown to the ion source researcher community.

Objective

- In this study, transverse beam emittance growth due to the inherent plasma instabilities present in a microwave ion source is investigated.
- Three type of plasma instabilities are demonstrated in the present study.

Plasma Instability

- Drift waves [2]
- Parametric decay instability (PDI)
- Instability from Multiple close frequency heating

- Effects of low frequency (LF) (kHz range) instabilities (drift wave and PDI) on transverse beam emittance is demonstrated through experiment.
- Beam oscillations extracted from the intensity data of Faraday cup inbuilt with the Allison type Emittance scanner.
- A correlation between the plasma instabilities and beam oscillations is obtained.
- In addition to the first two type of instabilities, another LF (MHz range) oscillations in beam appears under MCFH, also shows a strong correlation with the instability occurring in plasma sheath region.
- Finally, the appearance of MHz beam oscillations is tried to demonstrate with the help of microwave plasma simulation under similar experimental system and operating conditions.

Methodology

Experiment

Plasma

- Plasma instability identified in electromagnetic (EM) frequency emission from plasma
- Frequency (kHz-range) sidebands around pump MWs (2.45 GHz) is observed in emission spectra
- Two distinct sideband peaks appear at 1.3 MHz away from 2.45 GHz peak with similar intensity in overdense plasma.
- Two distinct peaks are excited cavity dependent resonant modes [1]
- Plasma emission captured at different power and fixed pressure.

Beam

- Beam emittance measured at same plasma conditions.
- Fast Fourier transform (FFT) of beam intensity obtained from inbuilt Faraday Cup
- Beam oscillations from FFT is correlated with plasma instability.

Simulation

- To validate kHz-range plasma drift waves, MW-plasma simulation performed in similar system configuration and operating environment [2].
- Plasma rotation with drift frequency is demonstrated in [1]
- To examine MHz-range oscillations, E-field in plasma and sheath is scanned in same COMSOL MW-plasma model.
- Interestingly, a strong inhomogeneity of E-field is seen within plasma sheath.
- E-field oscillations within the sheath thickness in MHZ range is found to arise.
- Finally, a footprint of strong inhomogeneous E-field in sheath layer is validated with the experimental evidence.

[1] C. Mallick et al., Rev. Sci. Instrum. 89, 125112 (2018)
[2] C. Mallick et al., Phys. Plasmas 26, 043507 (2019)

Experimental setup

- **Beam diagnostics**

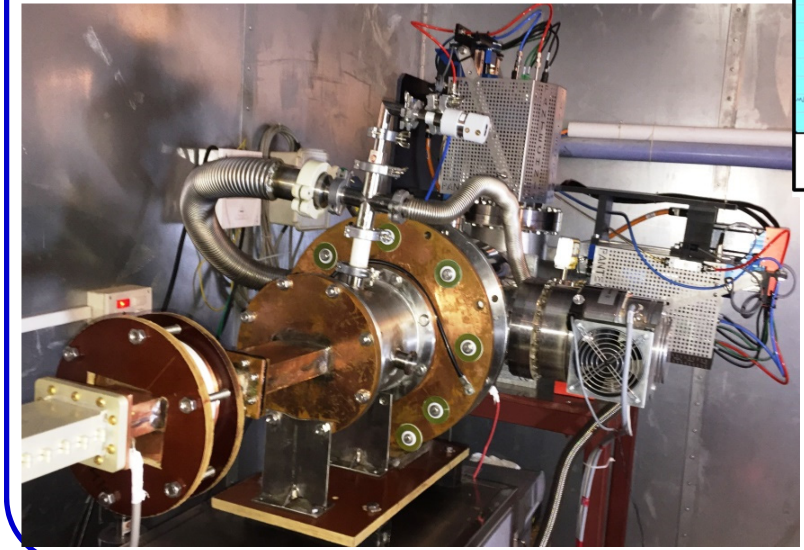
○Emittance study by Allison Scanner

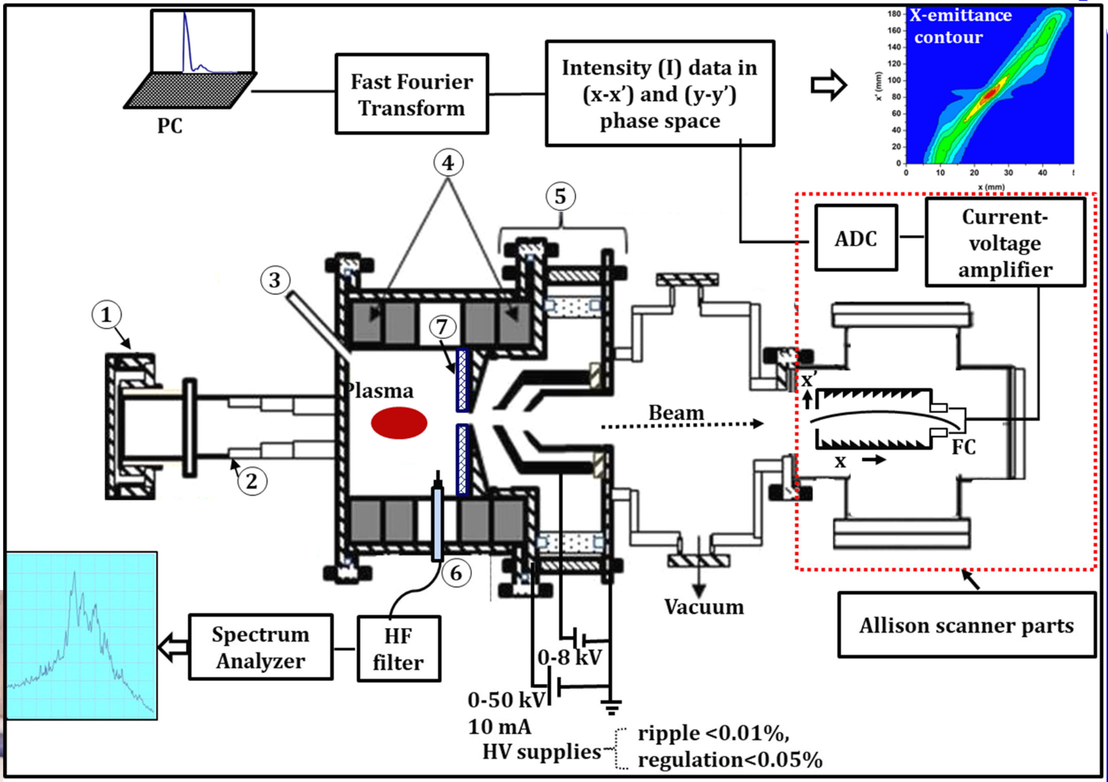
○Beam current obtained from Faraday cup

○Scanner position ~80 cm away from plasma grid

○ Inbuilt I-V amplifier
BW >200 kHz; sampling rate >1 MHz
Slew rate > 370 V/μs

○ Floating voltage~ 30 kV, acceleration voltage~300 V.





- **Plasma diagnostics**

○ RF circuitry (RF probe, HF cable, HF band-pass filter and a microwave Spectrum Analyzer

○ Operating conditions:
I/P power: 250 W-700 W and Pressure: 2-9$\times 10^{-4}$ mbar

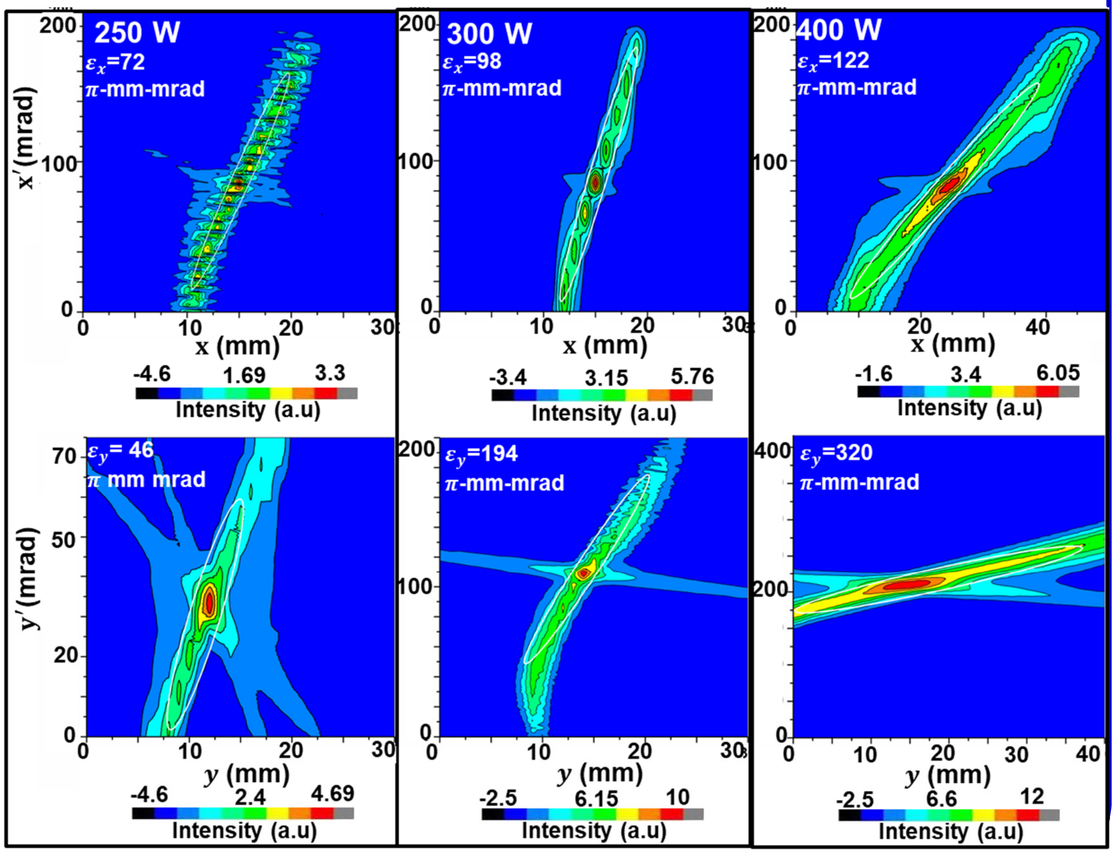
Preliminary experimental results

- ○ **Low power range (upto 250 W):**

1. **Transverse emittance variation is small (ε_x~80-96 Π mm mrad and ε_y~70-46 Π mm mrad**
2. **Above 250 W:**

   Emittance increases by 2-4 times (ε_x~190-210 Π mm mrad and ε_y~320-550 Π mm mrad

- ❑ **Plasma pressure ~2$\times 10^{-4}$ mbar**
- • **Beam line pressure~6$\times 10^{-6}$ mbar**
- • **For low energy beam, space-charge effect is negligible [1]**
- ❑ **Emittance increases with power**
- ❑ **Velocity of scanner head~ 10 nm/s**

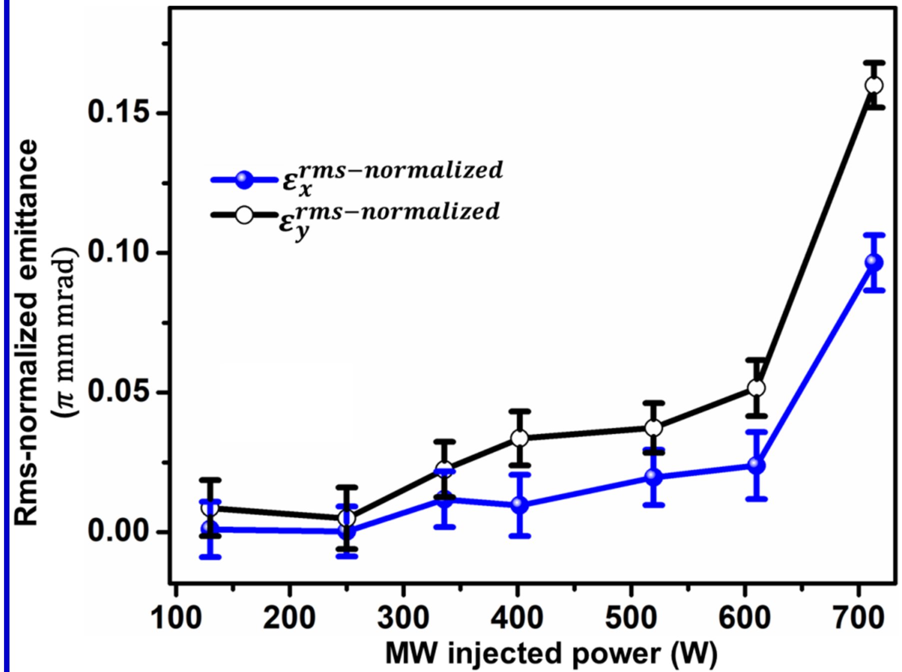


[1] N. Chauvin, "Space charge effect," in Proc. CAS, Senec, Slovakia, May/Jun. 2013, pp. 63–84.

[2] M. Strohmeier et al., Proceedings of BIW10, Santa Fe, New Mexico, US

Contd...Transverse emittance growth

- **Estimated beam emittance,**
  - $\varepsilon^{x-rms-normalized}$ **= 0.002-0.098 π mm mrad**
  - $\varepsilon^{y-rms-normalized}$ **~0.004-0.23 π mm mrad**
- **Ion temperature from emittance~28 eV**



[1] C. Mallick et al., Rev. Sci. Instrum. 89, 125112 (2018)
[2] C. Mallick et al., Phys. Plasmas 26, 043507 (2019)
[3] C. Mallick et al., 2nd revision submitted to Nucl. Fusion journal

Possible sources of emittance growth:

(a) Drift wave

- **Plasma rotation @$E \times B$ drift velocity**
- **Sharp fall of plasma potential near wall induces $E \times B$ drift**
- **Experimental $E \times B$ drift validated with simulation in [1-2]**
- **Frequency range: 360 kHz-600 kHz [1-2]**

(b) Parametric decay instability (PDI)

- **PDI of MW near mode conversion layer into ion waves**

(Demonstrated through experiment and simulation in [1-3])

- **Frequency range: 238-873 kHz [1-3]**

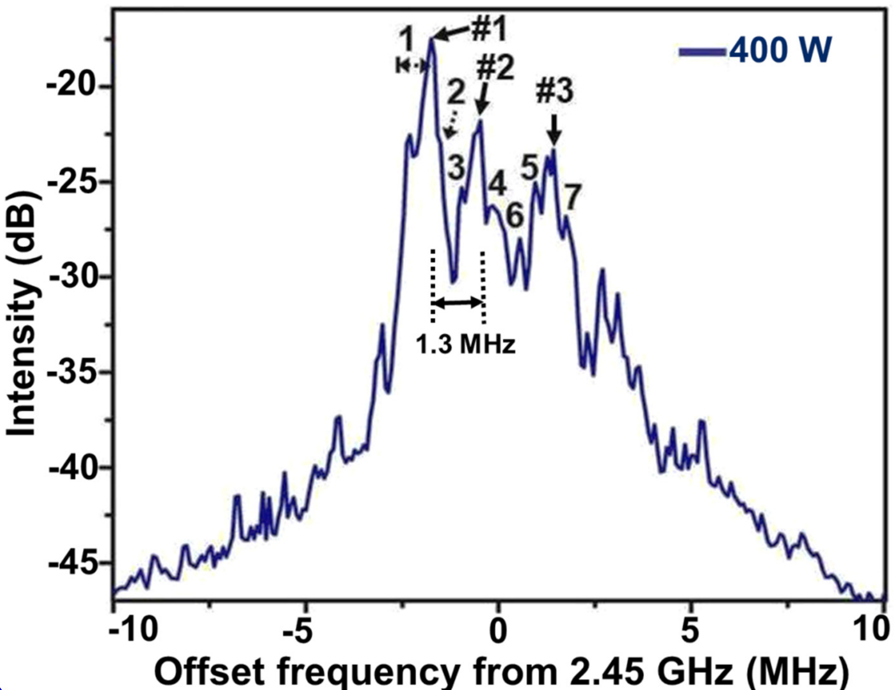
(c) Instability due to multiple closely spaced frequencies

- **Plasma perturbation due to multiple closely spaced cavity modes**
- **Strong inhomogeneous E-field within sheath layer**
- **Fast electrons' layer formation**
- **Frequency (1.3 MHz) determined from wave's penetration depth into plasma**

Continue…Experimental results

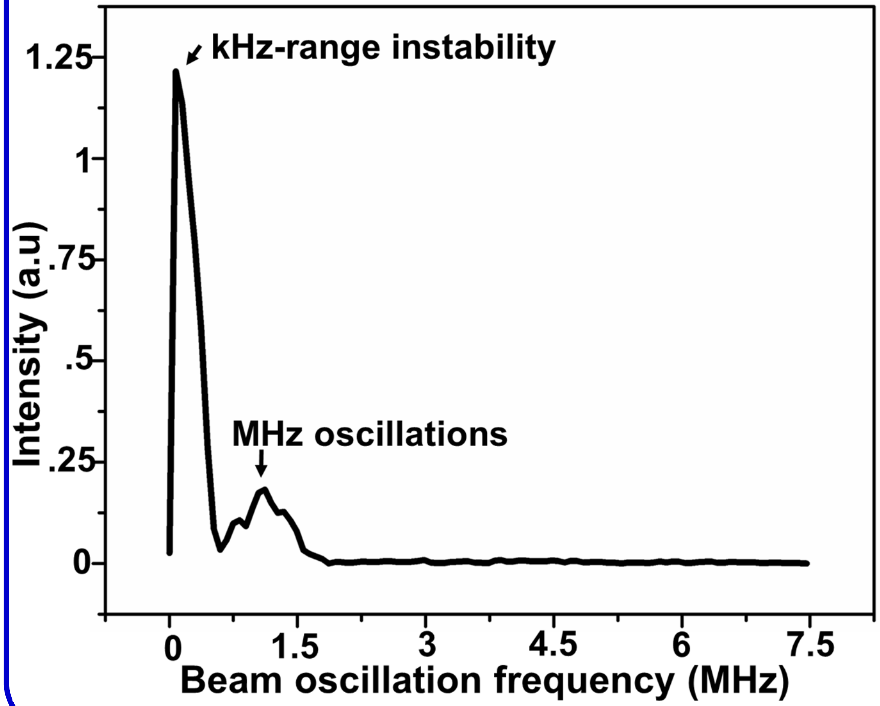
Plasma

- Plasma EM emission spectra
- Three distinct peaks corresponds to three excited cavity resonant modes (#1, #2 and #3) in plasma
- kHz-range (238-873 kHz) sidebands (named as, 1, 2, 3…)
- Two peaks spaced apart by 1.3 MHz



Beam

- kHz-range (476-873 kHz) beam oscillations
- 1.3 MHz oscillations in beam
- Beam oscillation frequencies are in the same order of sideband values in emission spectra



Theoretical analysis

- For example, in *X*-polarized MW,

Set of Maxwell's equations is simplified to modified Bessel's differential equations [1-3]

$H_z = A_1 I_m(Kr)$ (plasma region)

$H_z = A_2[J_m(\kappa r)N'_m(\kappa R) - J'_m(\kappa R)N_m(\kappa r)]$ (plasma sheath region)

Here $K^2 = (\omega/c)^2(\varepsilon_2^2 - \varepsilon_1^2)\varepsilon_1^{-1}$ and $\kappa^2 = (\omega/c)^2\, \varepsilon_s$ *and* $\varepsilon_1 = 1 - \Omega_\alpha^2/(\omega^2 - \omega_\alpha^2)$ and $\varepsilon_2 = \Omega_\alpha^2\omega_\alpha/\omega(\omega^2 - \omega_\alpha^2))$

- Condition $K^2 > 0$ possible waves in interface regions:

Region 1: $\omega_{LF} < \omega < |\omega_e|$; *Where* $\omega_{LF} = [\Omega_i^{-2} + (\omega_i|\omega_e|)^{-1}]^{-1/2}$ (1)

Region 2: $|\omega_e| < \omega < \omega_1 - |\omega_e|$, respectively. Here and $\omega_1 = 0.5\omega_e + [\Omega_e^2 + 0.25\,\omega_e^2]^{1/2}$ (2)

- In this experiment, for plasma parameters, n_i= 5.5$\times 10^{15}\ m^{-3}$ and 12$\times 10^{15}\ m^{-3}$, $B = 0.23\ T$ near the plasma boundary,

(a) ω_{LF} = 1.3 MHz waves obtained from eqn. (1)

- For plasma column and interface layer thickness of 44 mm and 1.62 mm, B = 0.26 T, ε_s=1, and n_e= 5.5$\times 10^{15}\ m^{-3}$ at the plasma-sheath interface region,

(b) Estimated frequency of waves~ 2.453 GHz which agree the experimental data.

[1] B. Jazi et al., , Plasma Phys. Control. Fusion 46 (2004) 507–518

[2] Girka, V. O. et al., Soviet Journal of Communications Technology and Electronics, Vol. 33, 37–41, 1988.

[3] Igor O. Girka et al., J. Plasma Phys. (2018), vol. 84, 905840603

Simulation results

- Simulation performed in similar experimental system configuration and operating environment

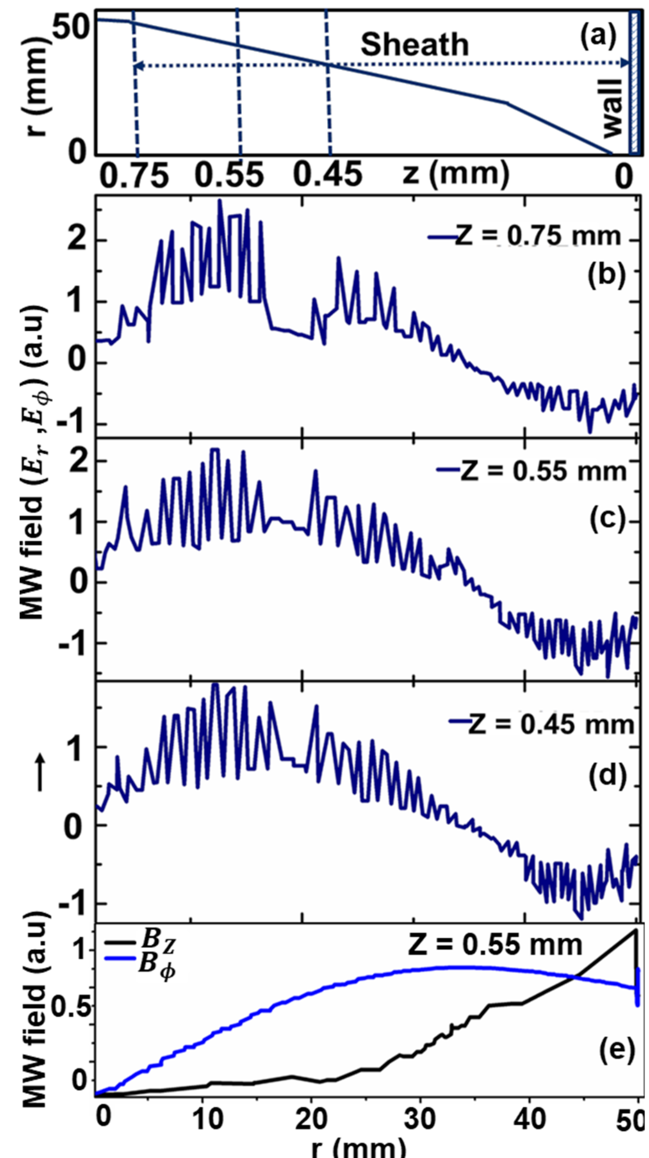
- A detailed description of MW-plasma COMSOL model given [1]
- A strong inhomogeneous E-field variation within sheath

  Scale size of inhomogeneity ~4-8 mm longitudinally; Gap between two inhomogeneous packet < 0.1 mm

- Strong inhomogeneous E-field within sheath ⟹ existence of fast electron layer because:
- Force exerted on electrons by high frequency(ω) wave field (E):

$$F_{avg} \propto \frac{(\omega_0^2-\omega^2)}{(\omega_0^2-\omega^2)^2+\gamma^2})\nabla(E^2)_{avg}$$

For $\omega \gg \omega_0$ (i.e., atomic coupling or plasma resonance), $F_{avg} \propto \nabla(E^2)_{avg}$ ⟹ Volume heating ⟹ fast electrons [2-4]



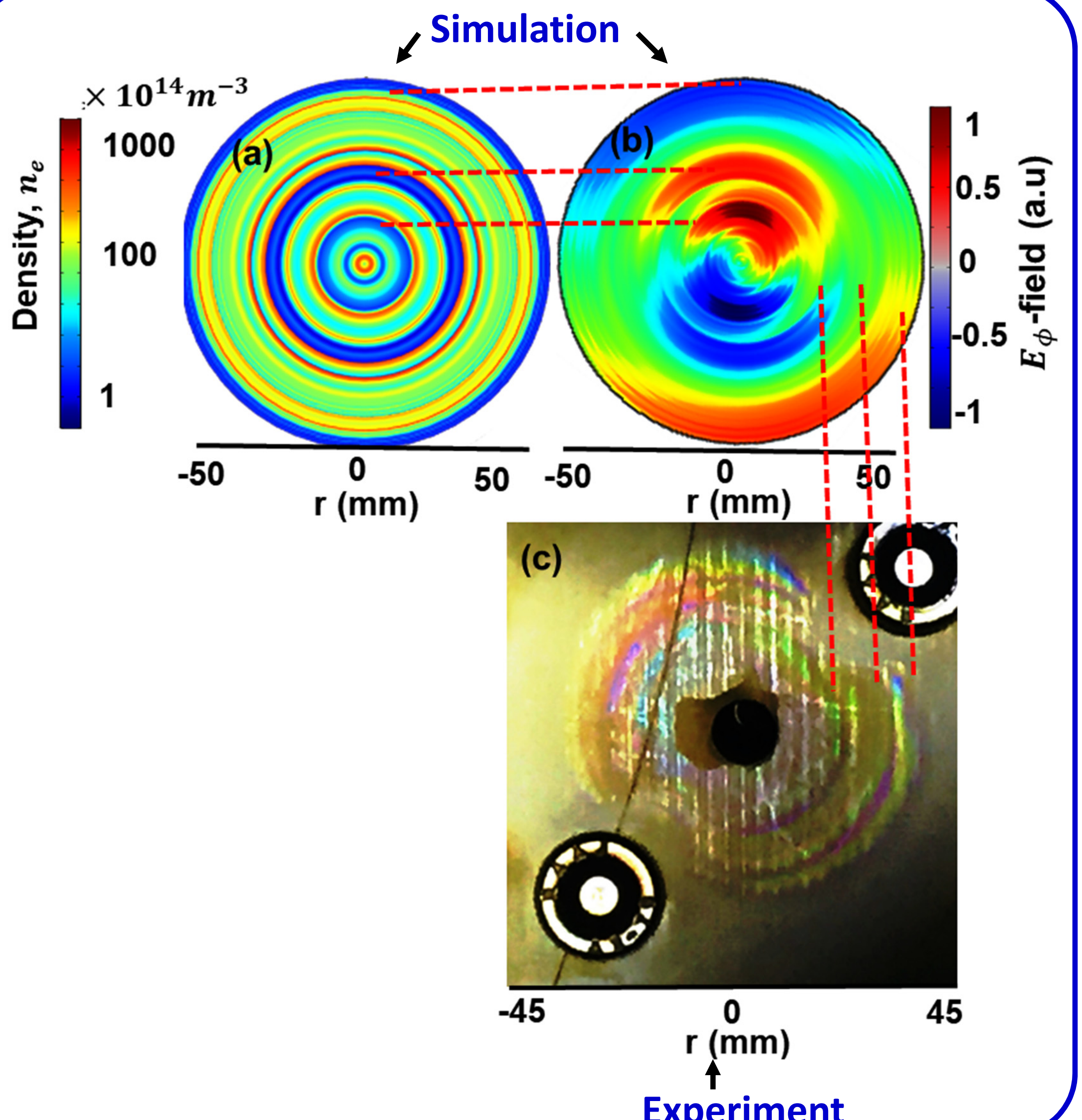
[1] C. Mallick et al., Phys. Plasmas 26, 043507 (2019)

[2] Moisan M. and Leprince P., 1975 Beiträge Plasmaphysik 15 83–104
[3] G. A. Askar'yan, Sov. Phys. JETP 15, 943 (1962)
[4] Yu M Alievt, V Yu Bychenkovt, A V Maximovt and H Schluter, Plasma Sources Sci. Technol. 1 (1992) 126-131

Footprint of fast electrons on Boron nitride insulator plate: Verify experiment with simulation

NAPAC2019 North American Particle Accelerator Conference: 1-6 September 2019

- Simulation plot on plasma-insulator interface or within the Plasma sheath
- 2D Surface plot (a) Density layers and (b)E-field $r - \phi$ variation
- Strong inhomogeneous E-field creates fast electrons at the interface of density layers
- Interaction of fast electrons with insulator surface
- Below experimental 2D surface plot ➡ Similar footprint of fast electron layers on Boron nitride plate surface (inside picture taken by camera)



Summary

- kHz-range instabilities (drift wave and PDI) increases the transverse beam emittance
- Another MHz-range oscillations in beam is observed
- Impacts of MHz unstable wave present in plasma on beam emittance growth is more significant than other two type of instabilities.
- A correlation between instabilities occurring in plasma and beam oscillations is found
- Excited cavity dependent resonant modes may be responsible in producing MHz beam oscillations
- Evidence of experimental results supported by simulation envisages that excited cavity resonant modes may produce strong inhomogeneous electric field within the plasma sheath.

Thank You for your time!!!

Complete experimental setup