CHEA Meeting
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Does Plasma Oscillation Radiate?

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Collaboration with

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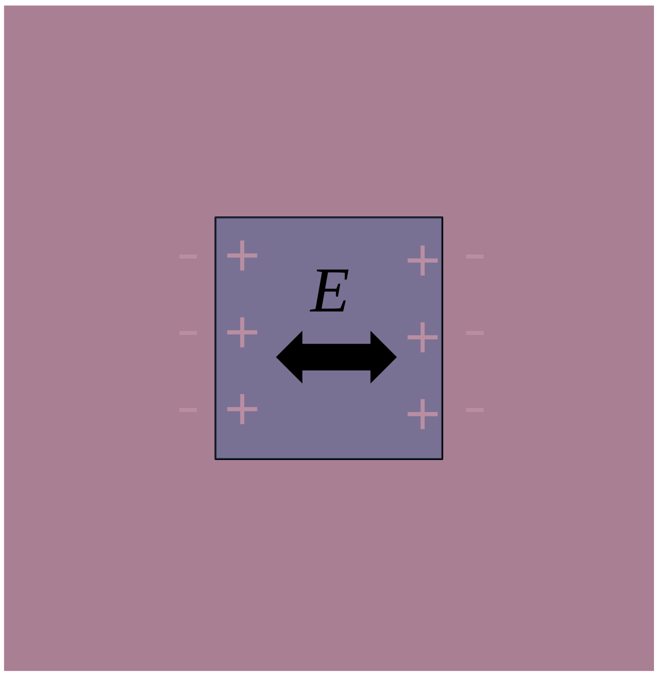
Outline

- Review of the controversy on the radiation from plasma oscillation
- New Research
- Future work

Plasma Oscillation

Harmonic oscillation of a solid-like electron block



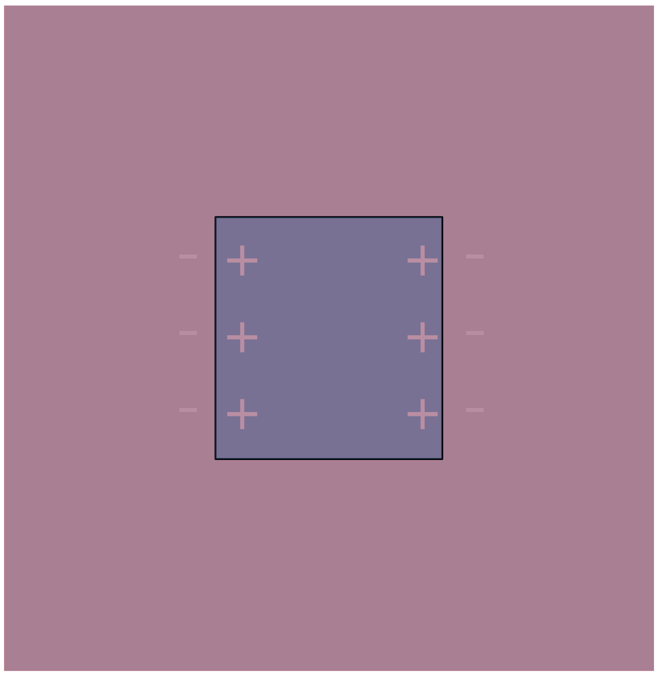
$$-\frac{e n_0}{\varepsilon_0}\Delta x = E$$

$$m\Delta\ddot{x} = eE = -\frac{e^2 n_0}{\varepsilon_0}\Delta x$$

$$\Delta\ddot{x} + \frac{e^2 n_0}{m\varepsilon_0}\Delta x = 0$$

$$\omega_p = \sqrt{\frac{e^2 n}{m\varepsilon_0}}$$

Harmonic oscillation of a solid-like electron block



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Oscillating Electrons will Emit Radiation

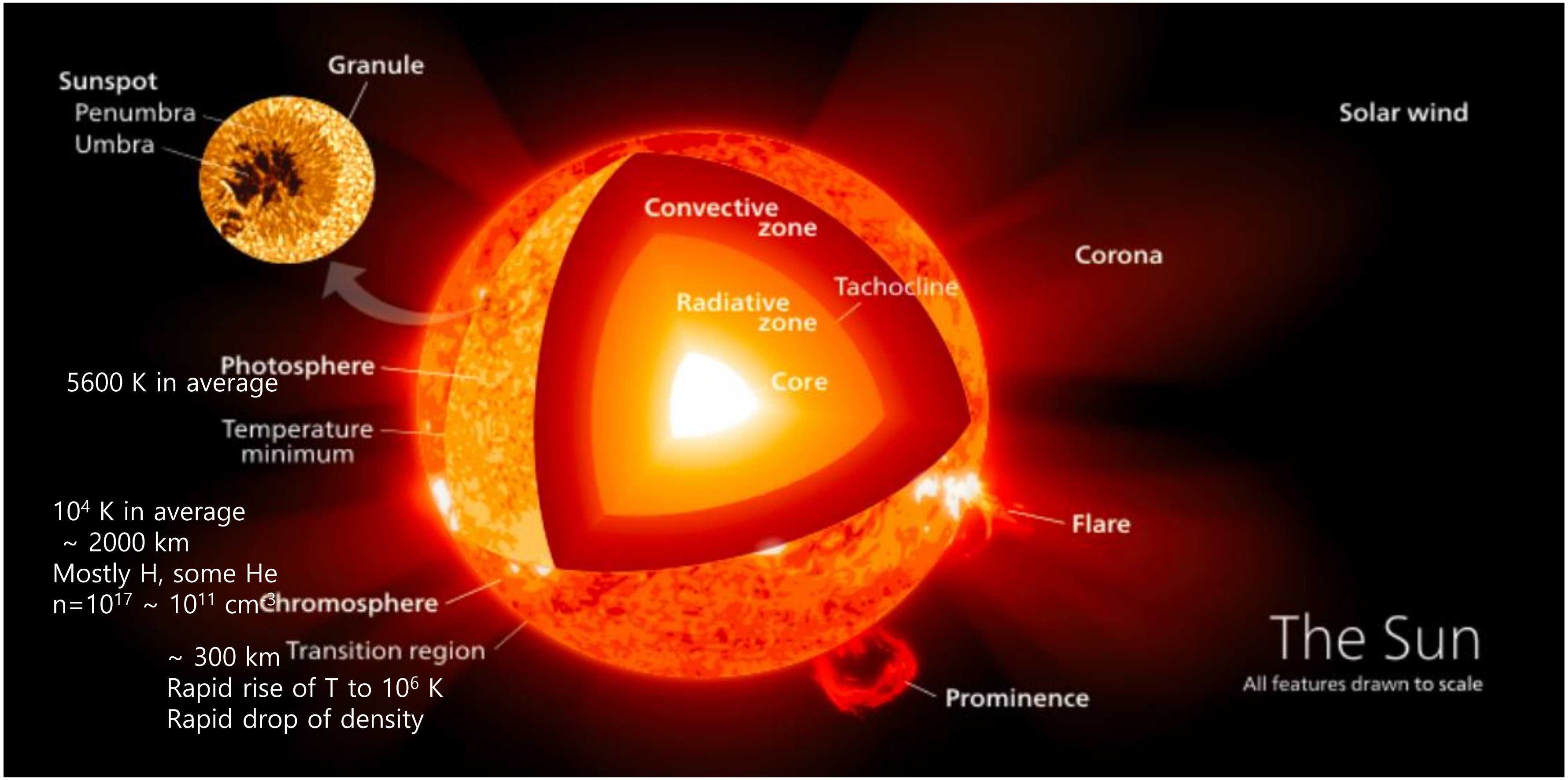
Advantages as a Radiation Source

- Readily tunable by changing the plasma density
- Can cover an extremely broad spectral range from microwave to XUV
- Well-collimated radiation: just a dipole radiation
- High spatial coherence: no angular-dependence of the spectrum
- Monochromatic: high temporal coherence

In the astrophysical context,

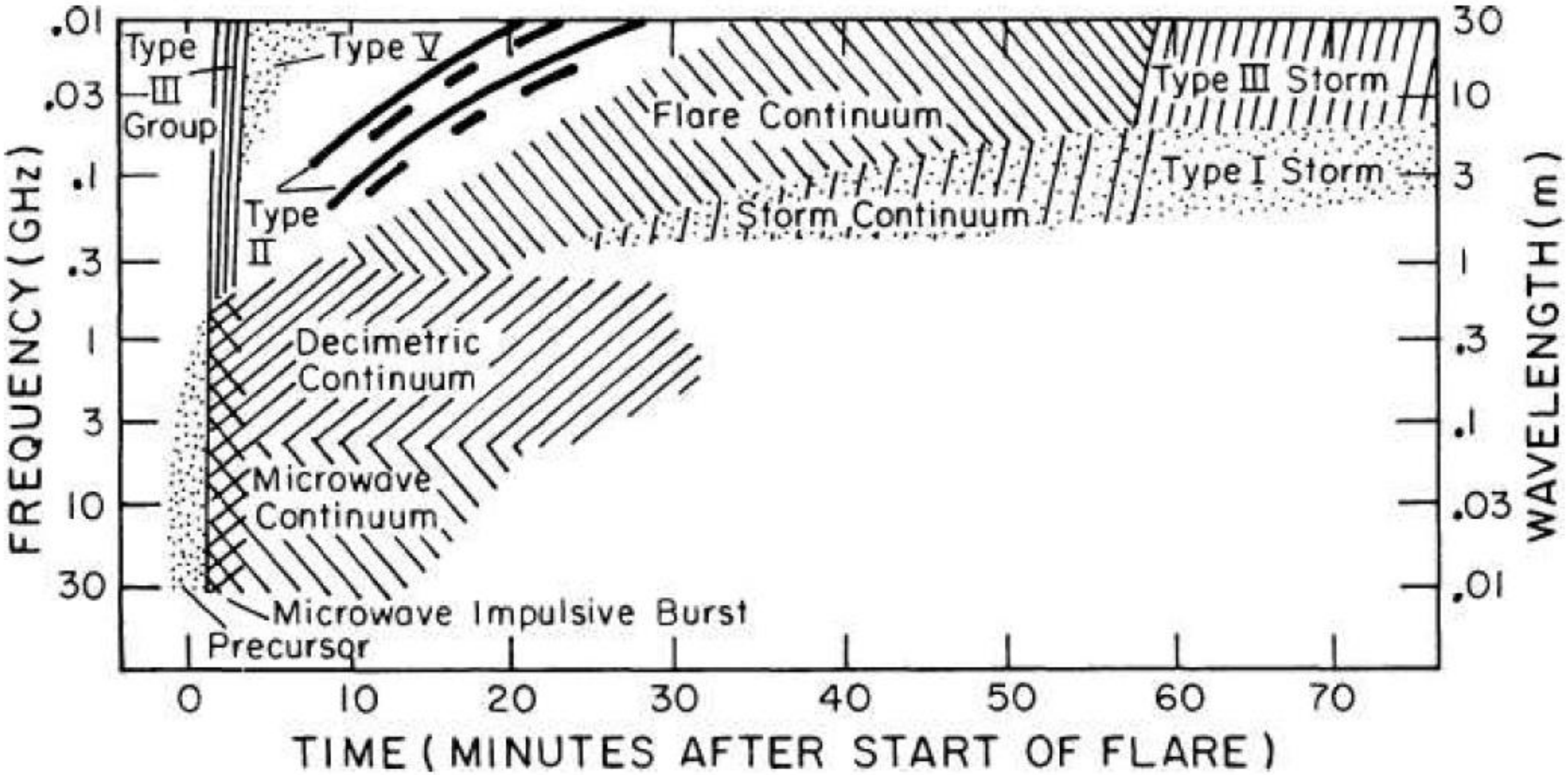
- Plasma oscillation is the major origin of coherent radio-bursts from solar corona.
- Plasma oscillation (actually Langmuir wave) is generated by electron beam accelerated from magnetic reconnection or shock near the surface of the Sun.

Layers above the Solar Surface



*Temperature rising in transition region and corona is still not fully understood.

Radiation Bursts from Sun



G.A. Dulk, ARA & A 23, 169 (1985).

Coherent Radiation Burst from Sun

Type III Radio Bursts

- Lasts several tens of minutes.
- Fast frequency drift.
- Originates from the solar Corona.
- Generated by e-beam-driven Langmuir wave (plasma wave).

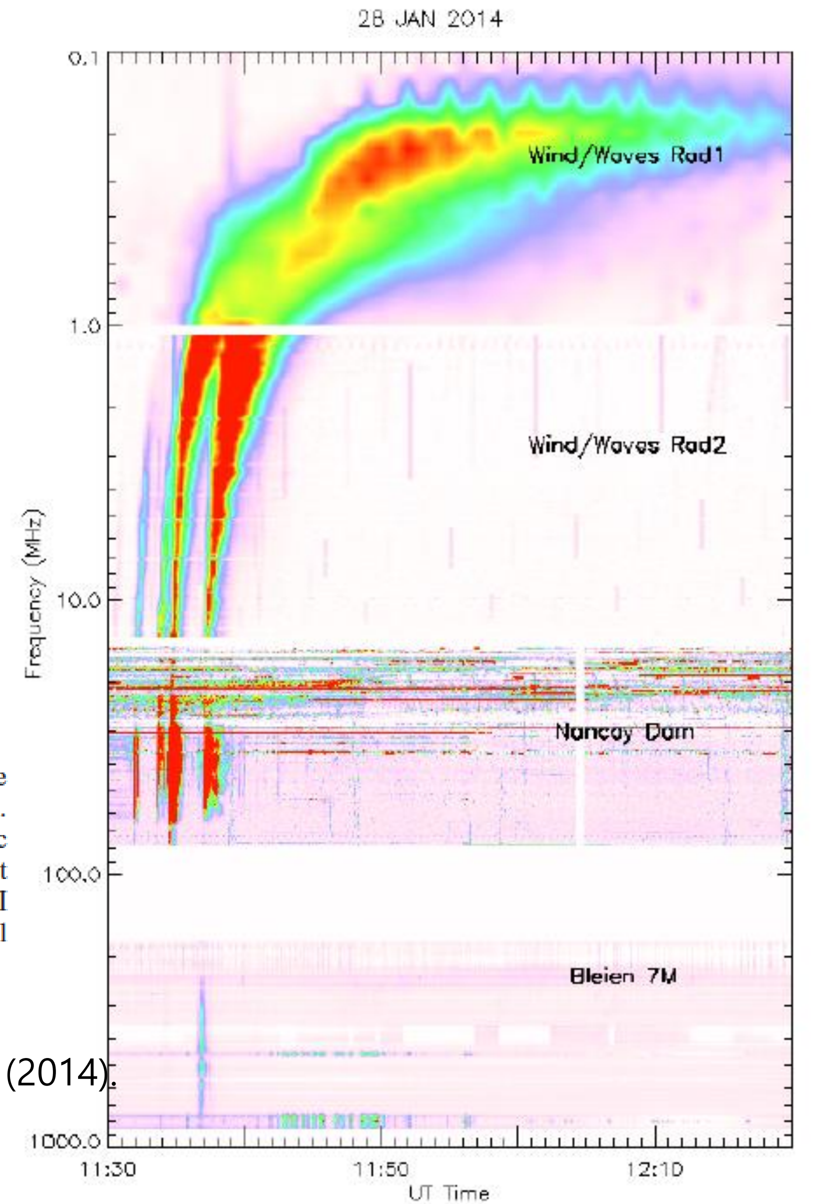
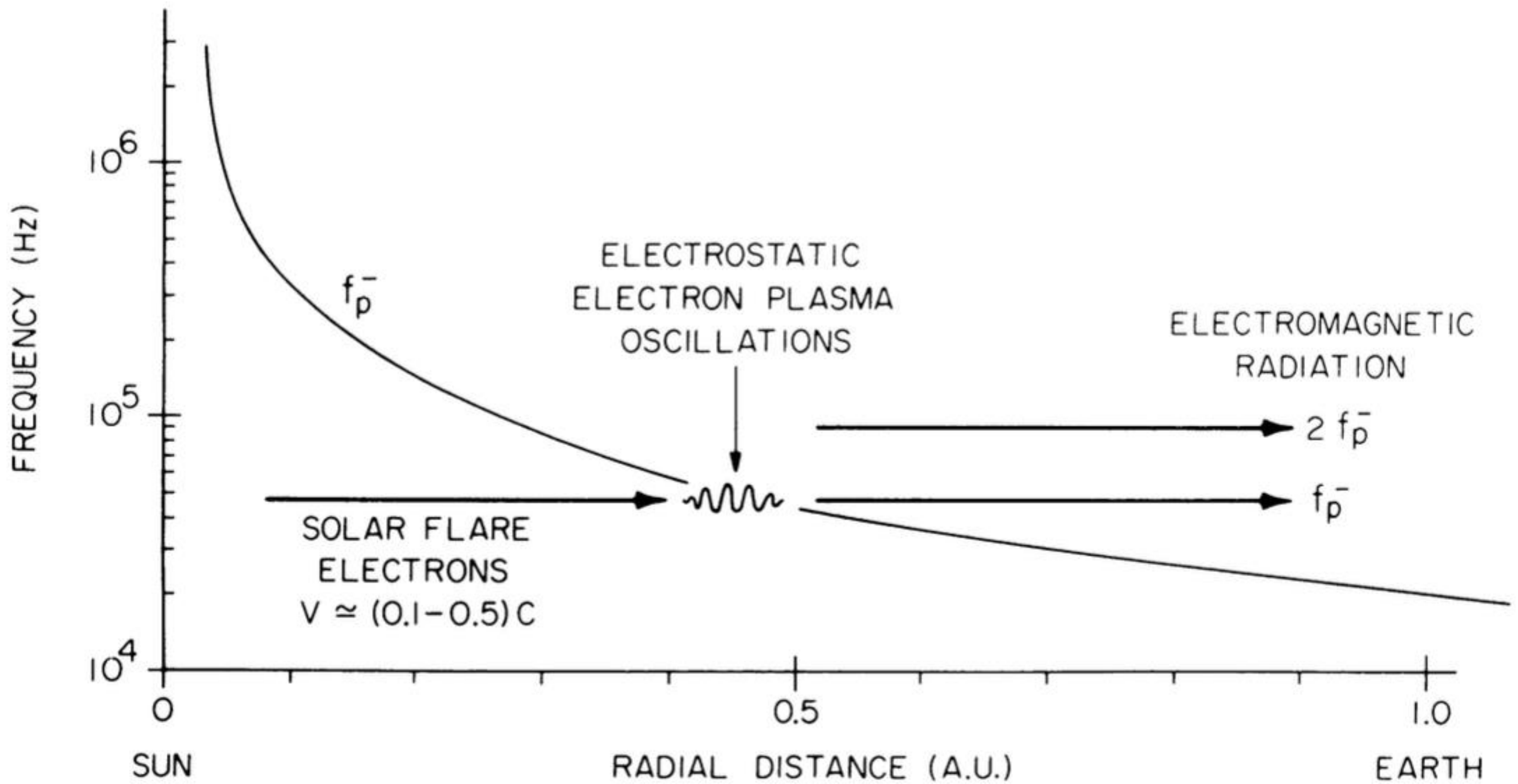


Fig. 1 An example of a dynamic spectrum from an interplanetary type III radio burst observed on the 28th January 2014. The 900–200 MHz frequencies are observed by the Bleien telescope (Benz et al. 2009a). The 80 to 15 MHz frequencies are observed by the Nancay (with the cedilla) Decametric Array (Lecacheux 2000). The 14 to 0.1 MHz frequencies are observed by the WAVES experiment onboard the WIND spacecraft (Bougeret et al. 1995). You can see a number of different type III bursts starting at different frequencies from < 100 MHz at 11:32 UT to > 1 GHz at 11:37 UT. All the radio bursts merge into one at the lowest frequencies of < 1 MHz.

H.A. Reid & H. Ratcliffe, Res. Astronomy & Astrophys. 14, 773 (2014).

Frequency Drift of Type III



Gurnett, et al., *Plasma oscillations and the emissivity of type III radio bursts*, Radio Physics of the Sun by Kundu and Gergely, p. 369-379, 1980

Narrowband Spikes in Type III

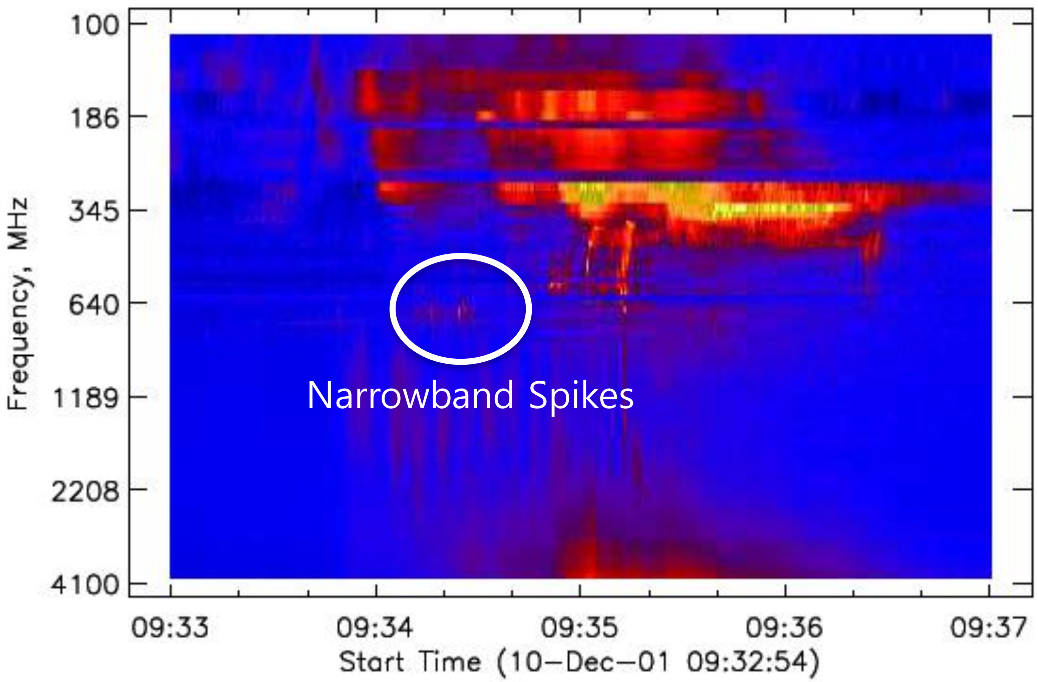
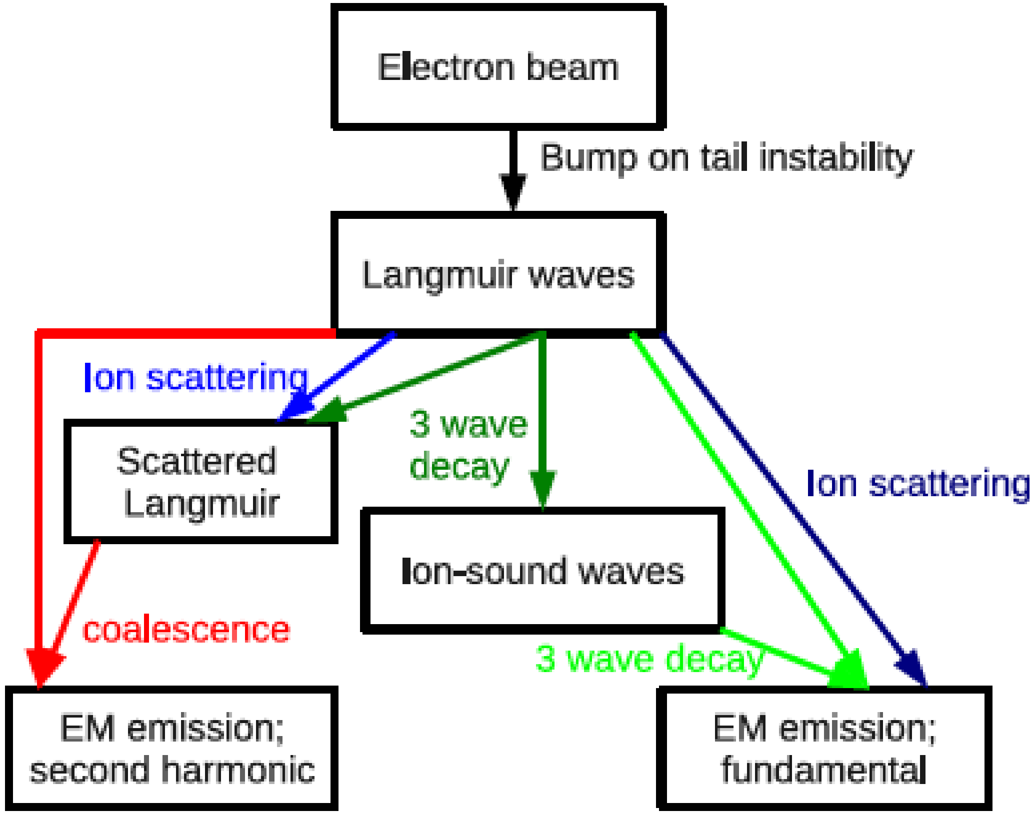


Figure 1.3: An example radio dynamic spectrum from the Phoenix-2 spectrometer. After Benz (2004). The horizontal bands around 186, 300 and 600 MHz are from terrestrial interference.

H. Ratcliffe, Doctoral Thesis, and also in arXiv:1307.1321v

- Lasts just for a few seconds.
- Narrowband spectrum.
- Not fully explained yet.
- Should be originating from a very limited region in the corona.
- The PDO can be relevant.

Electron beams are accelerated from flares or shocks



D.B. Melrose, 2009, in IAU Symposium, Vol. 257, IAU Symposium, ed. N. Gopalswamy & D. F. Webb, 305–315

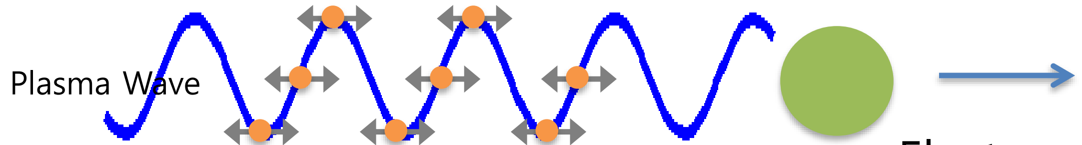
However,

- Radiation from the plasma oscillation is a controversial issue, at lea st in laboratory plasmas.
- The controversy is partially due to the fact that

Mostly the plasma oscillation exists as a part of plasma waves!

Plasma Oscillations exist as parts of a Plasma Wave (Langmuir Wave)

Plasma Wake Wave

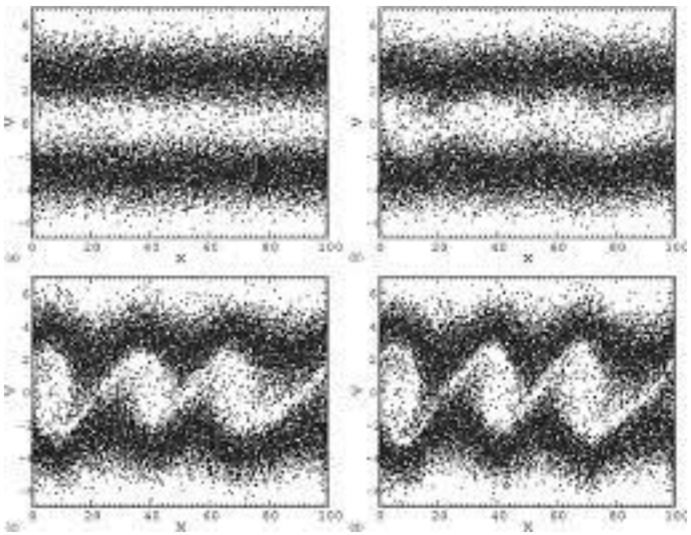


Electron beam or Laser pulse

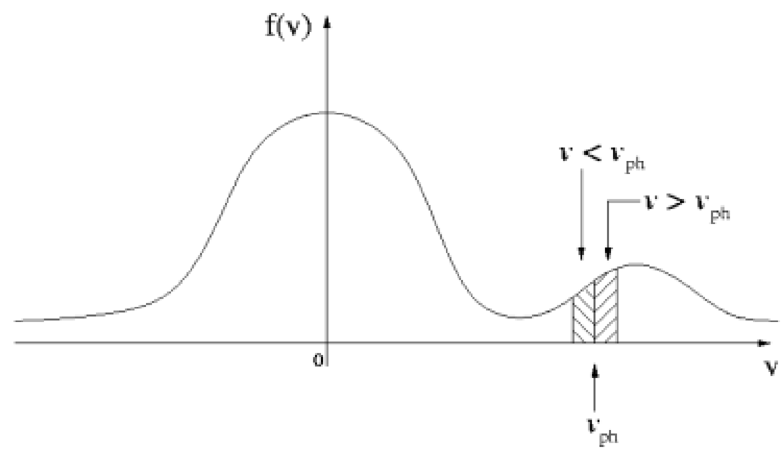
Ship Kelvin Wake

Plasma Wave

Stream Instability of an Electron Beam generates a Langmuir Wave



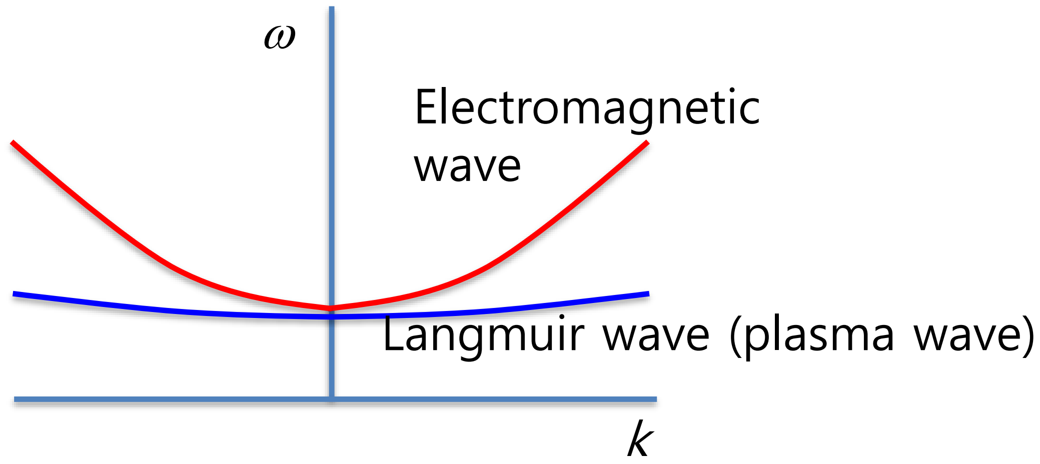
S.Y. Ha et al., J. Math. Phys. 2011



Wikipedia – Two-stream instability

Non-Radiating Homogeneous Plasma Wave

No crossing of dispersion curves except at k=0, where v_g=0.



Note: resonant energy exchange between two wave modes occurs when their (k,w)'s are identical.

Non-Radiating Homogeneous Plasma Wave

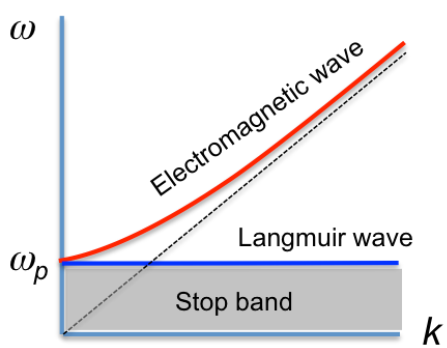
Other Arguments of non-radiating plasma wave

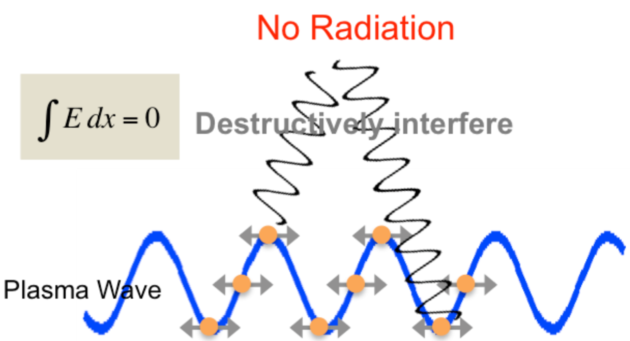
- The electric field of a plasma wave driven by laser is curl-free (V. Tikhonchuk, PRL'02, PRE'16).
- The driving current is curl-free (J. Meyer-ter-Vehn, EPS Conf. '09).
- The phase velocity of a plasma wave driven by laser is slower than the speed of light in vacuu m (P. Sprangle, PRE'04).
- "The radiation at the plasma frequency is near cut-off, and is strongly absorbed." (Yoshii, Katsou leas, PRL'97).
- Radiation from each electrons destructively interferes (MS Hur, unpublished).
- It is possible to find an inertial reference frame where the plasma wave looks stationary (TY Kan g, unpublished).
- And so many others.

$$\nabla \times \vec{E} = 0 \;\rightarrow\; \vec{B} = 0$$

$$\nabla \times \vec{J} = 0 \;\rightarrow\; \text{No radiation}$$

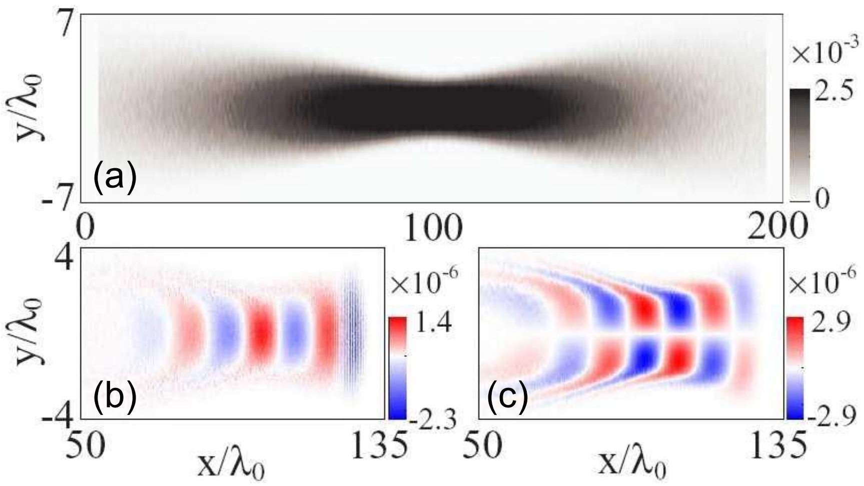
* Radiation is driven by rotatio nal current only.

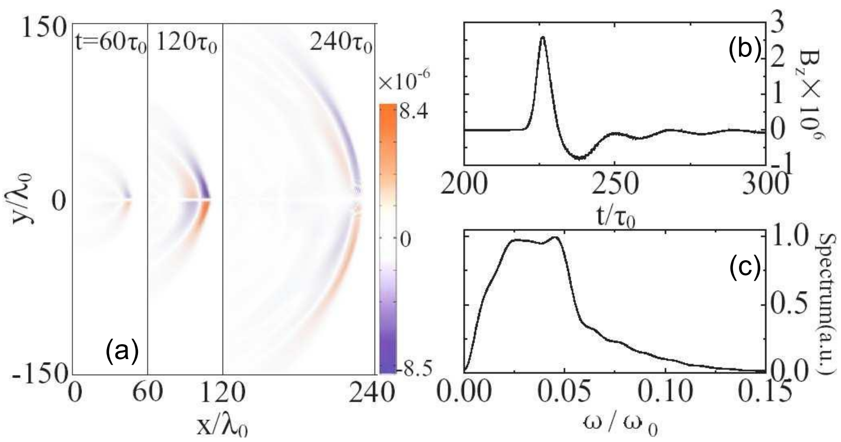




Filamented Plasma by a single laser pulse

- Make the plasma Inhomogeneous



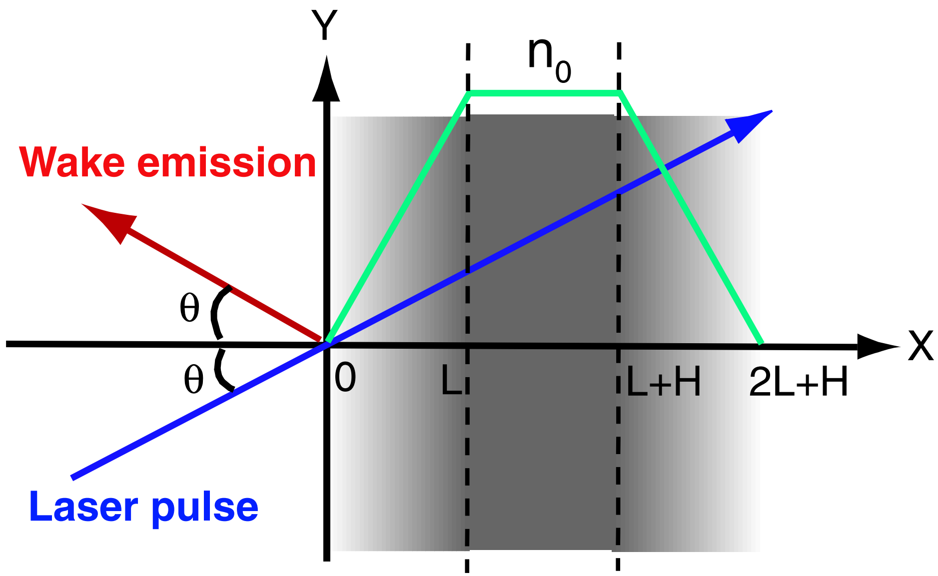


H.C. Wu & J. Meyer-ter-Vehn, 36th EPS Conf.

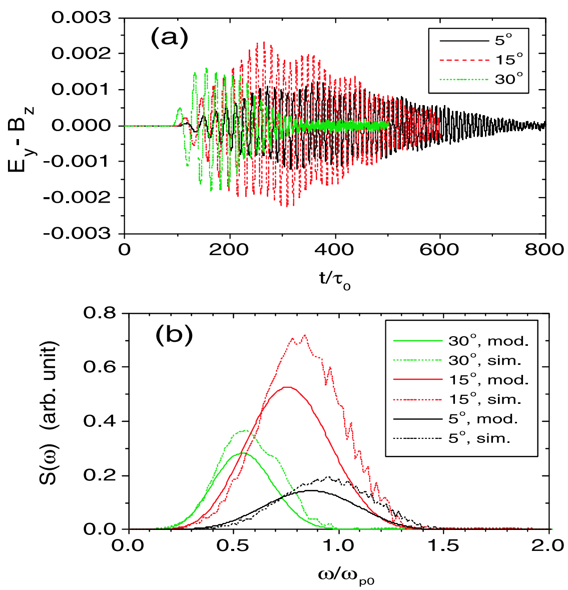
- The Radiation is emitted near the filament end, where a certain level of non-destructive wave and also non-zero curl E survive.
- However, the wave is not quite at the plasma frequency.

Linear Mode Conversion

- Inverse process of the resonance absorption



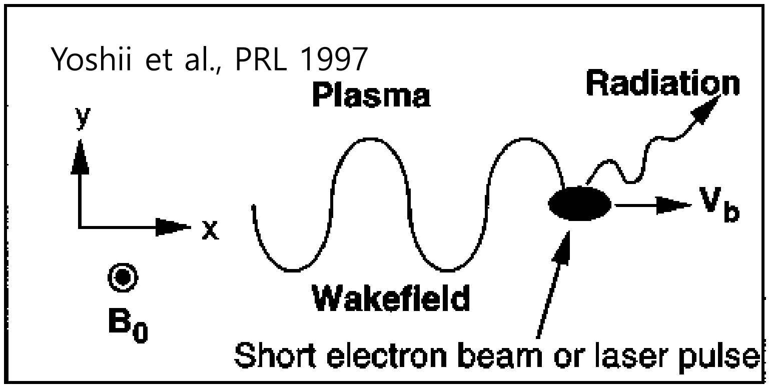
Z.M. Sheng et al., PRL 2005



- Non-zero transverse component of the plasma oscillation is responsible for the Radiation emission.
- Curl E can be non-zero in inhomogeneous plasmas

Radiation from a Magnetized Plasma (Cherenkov Wake)

- Inverse process of the resonance absorption



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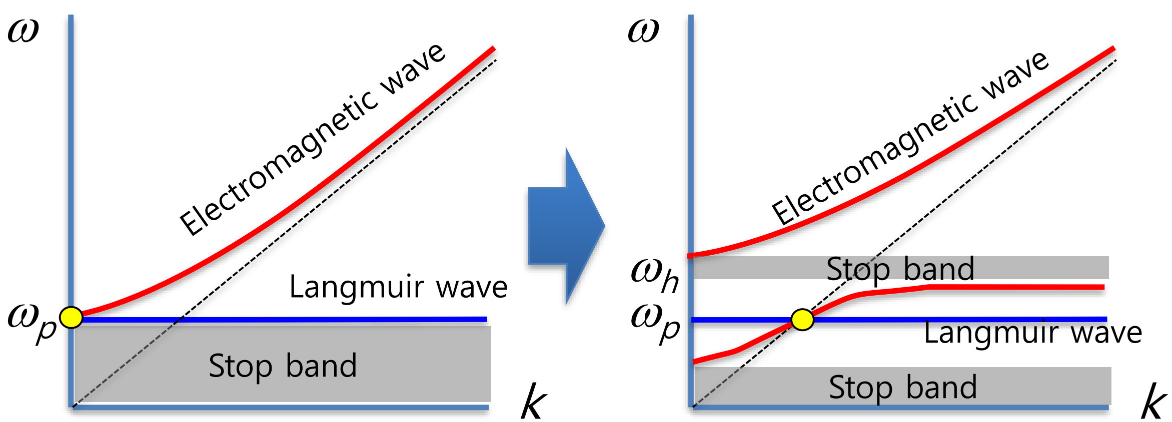
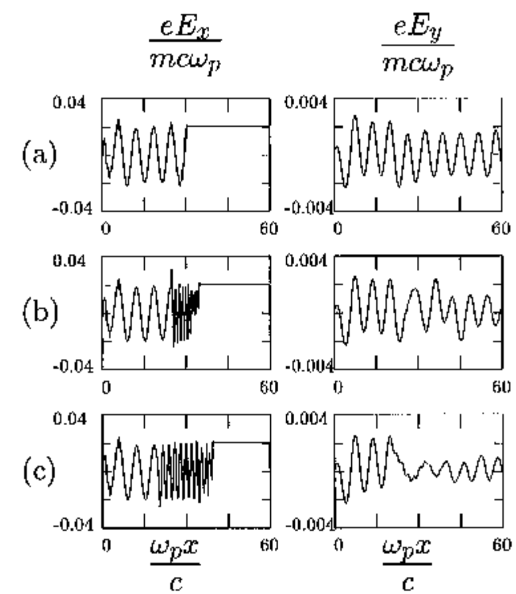
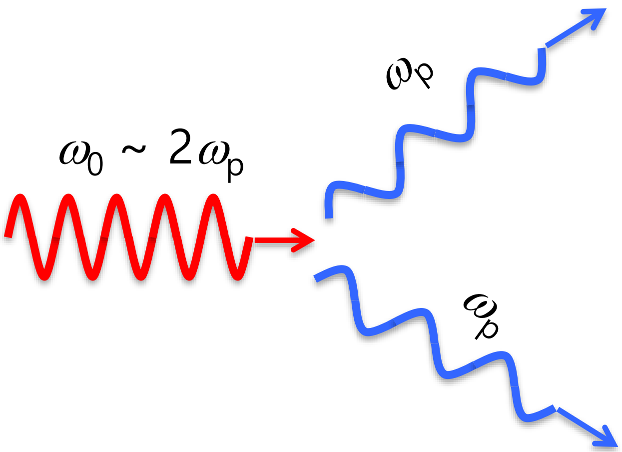


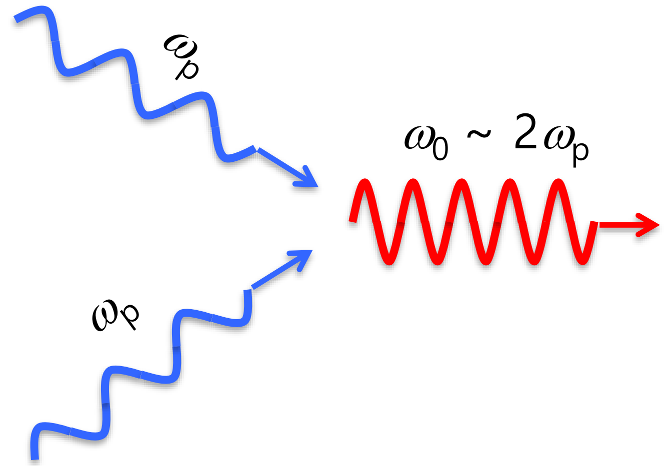


Radiation by Decay Instability

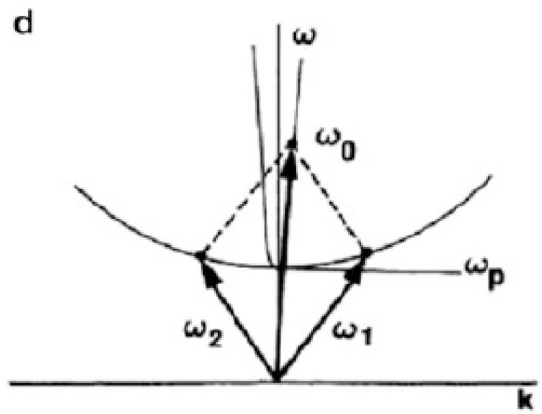
Coalescence of Two Plasmons for 2nd Harmonic Generation



F. Chen, Intro. Plasma Phys. Controll. Fusion



Melrose,



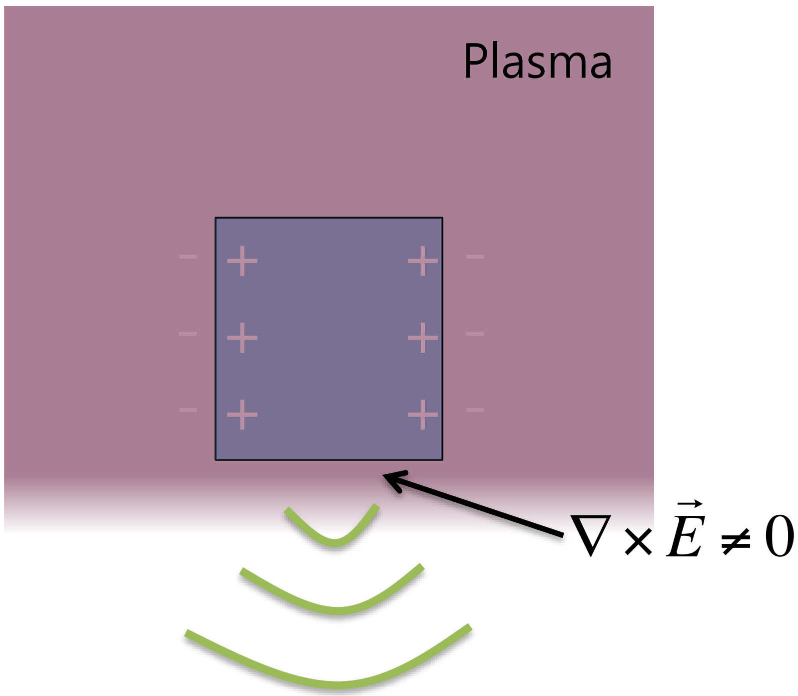
Inverse of two-plasmon decay leads to generation of the 2nd harmonic ($2\omega_p$) radiation.

Players of the Controversy

	Homogeneous	Inhomogeneous	Refs.
Tikhonchuk, Sprangle	No	Seems to want to say 'No'	PRE, PRL
Sheng, Liao, Meyer-ter-Vehn	No	Yes	PRL,
MS Hur, Jaroszynski	**Yes**	Yes	Non-published

Plasma Dipole Oscillation (PDO)

PDO + Inhomogeneity leads to Radiation Emission



Obviously, $\nabla \times \vec{E} \neq 0$ at around th
e
dipole boundary. The dipole field can
radiate.

In a homogeneous plasma, the radiation is cut-off by the ambient plasma.
* This assumption will be broken later in this presentat
ion

PDO located close to the plasma-vacuum interface, the radiation can be extracted.

PDO Model has been just Pedagogical

Lecture note from OCW, MIT

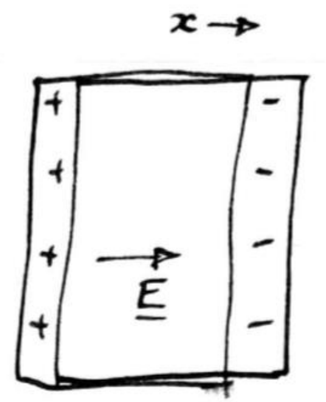


Figure 5.1: Slab derivation of plasma oscillations

Equation of motion of electrons

$$m_e \frac{dv}{dt} = -\frac{n_e q_e^2 x}{\epsilon_o}; \tag{5.48}$$

i.e.

$$\frac{d^2 x}{dt^2} + \left(\frac{n_e q_e^2}{\epsilon_o m_e}\right) x = 0 \tag{5.49}$$

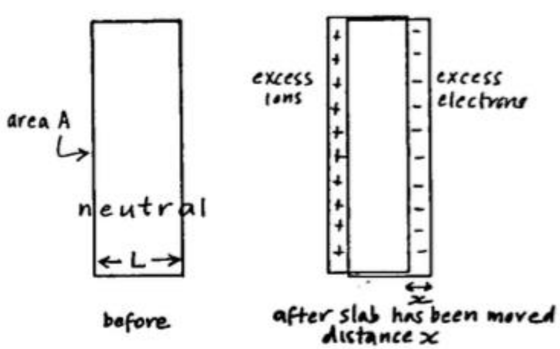
PDO Model has been just Pedagogical

Lecture note from Physics, University of Sydney

A simple calculation of the frequency follows.

Consider an infinite plasma. We will ignore thermal motions. We will treat the massive ions as not moving.

Suppose a slab of electrons is displaced a small distance x (so we are dealing with a 1-dimensional problem). The slab has thickness L. Consider an area A.



Equation of motion for the slab of electrons is $F = m\dfrac{d^2x}{dt^2}$

mass of electrons in slab $m = m_e n_e L A$

PDO Model has been just Pedagogical

W. Baumjohann and R.A. Treumann, *Basic Space Plasma Physics*, Imp. College Press, London, '96

M.A. Lieberman and A.J. Lichtenberg, *Principles of Plasma Discharges and Material Processing*, A Wiley-Interscience Pub.

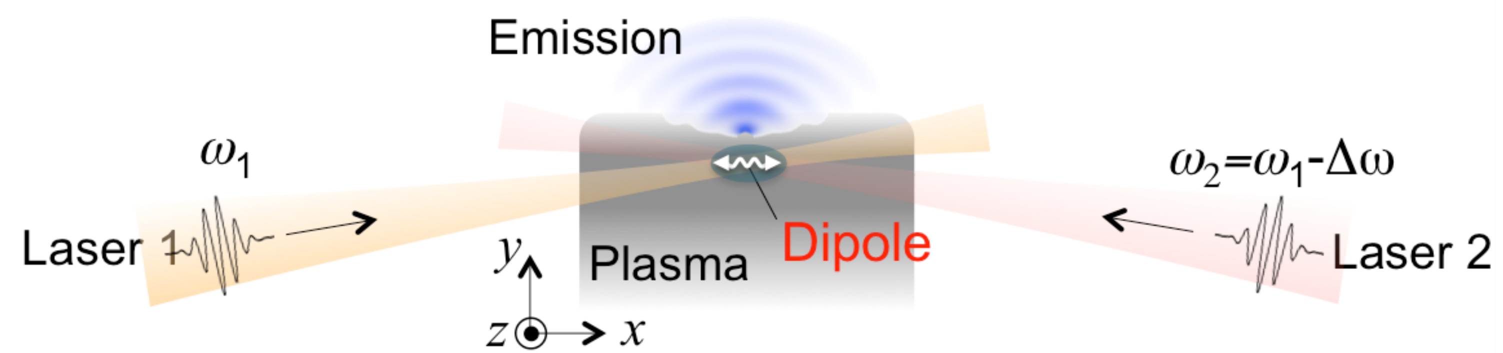
M. Gedalin, *Lecture Notes in Physics, Introduction to Plasma Physics*, Ben-Gurion Univ., Israel.

The PDO is popularly used for education. However,

The PDO is NEVER trivial !

- No good method of generating PDO has been known so far.
- Stability and radiation characteristics have not been known either.

Generation of PDO



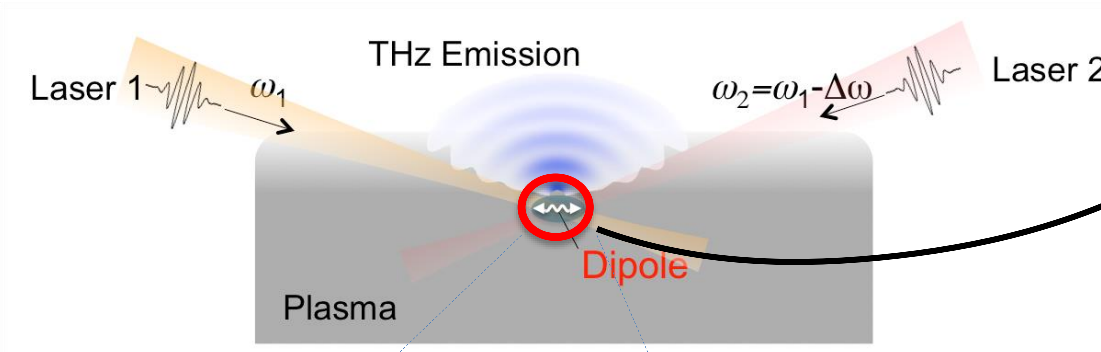
At the collision point of two detuned laser pulses,
a strong plasma dipole oscillation (PDO) is generated.

Mechanisms of PDO-generation

1. DC component of the nonlinear current (weak driver regime)
   Cho et al., New J. Phys. 17, 043045 (2015).

2. Trapped particles on the moving potential train (strong driver regime)
   Kwon et al., arXiv:1612.00229 (2016).

PDO by Trapped Particles

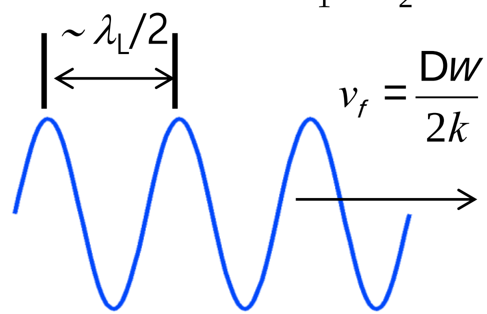


Moving Potential Train

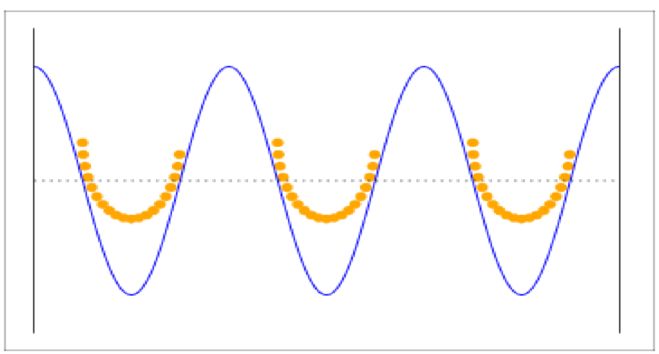
$$F_{PM} \sim I_{laser} e^{2ikz - i\Delta\omega t}$$

$$\Delta\omega = \omega_1 - \omega_2 << \omega_{1,2}$$

$$2k \equiv k_1 + k_2$$



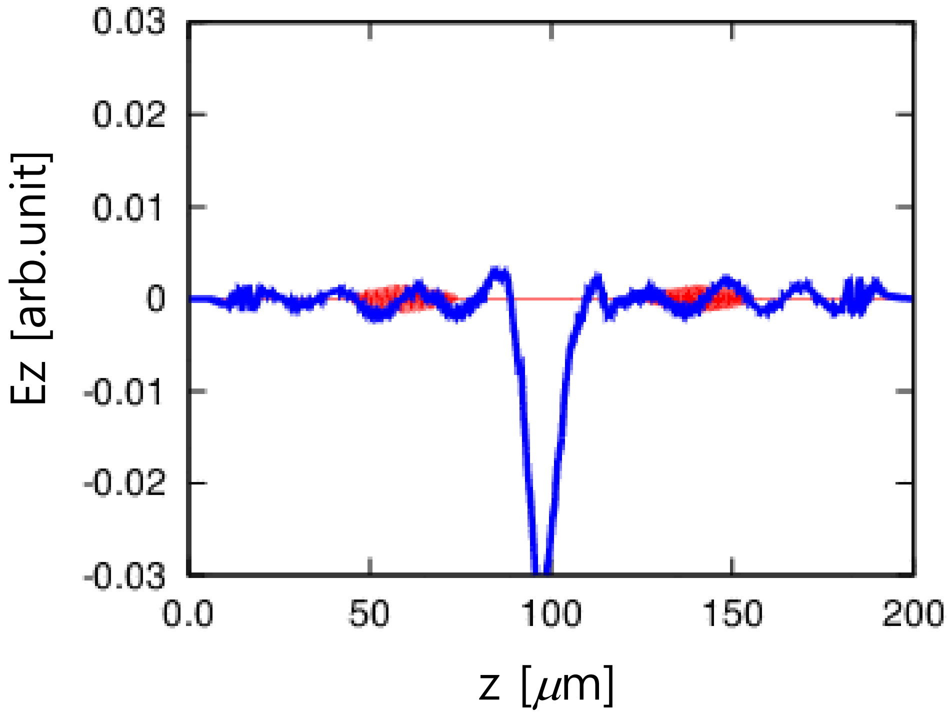
$$v_f = \frac{\Delta\omega}{2k} = \frac{\omega_1 - \omega_2}{k_1 + k_2} << c$$



Electrons riding on the potential trai
n
are displaced in a block to the right

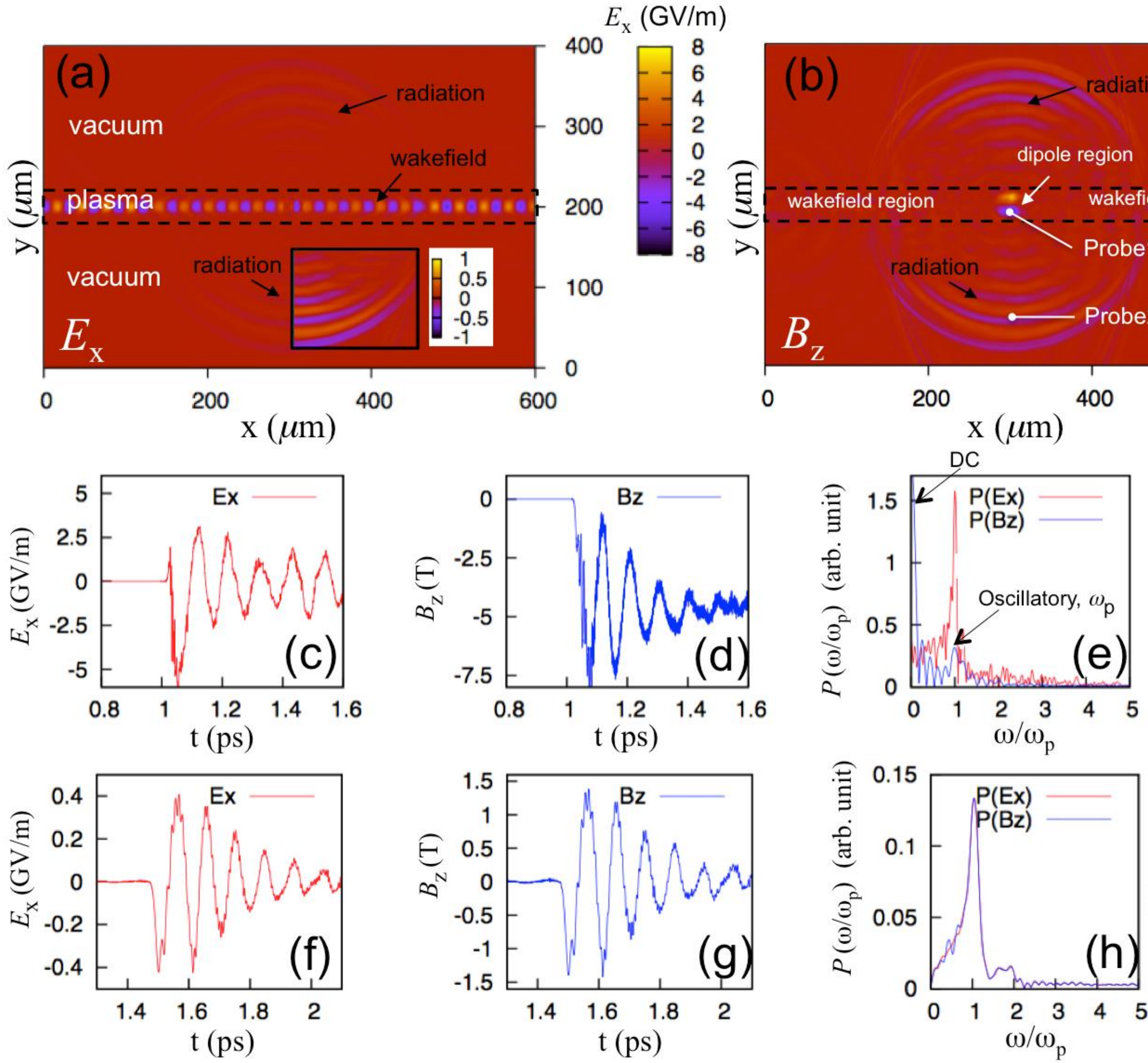
Velocity of the displacement is
determined by the laser detuning $\Delta\omega$

One-dimensional PIC simulation of building-up the Dipole



Red: Laser field
Blue: Plasma field

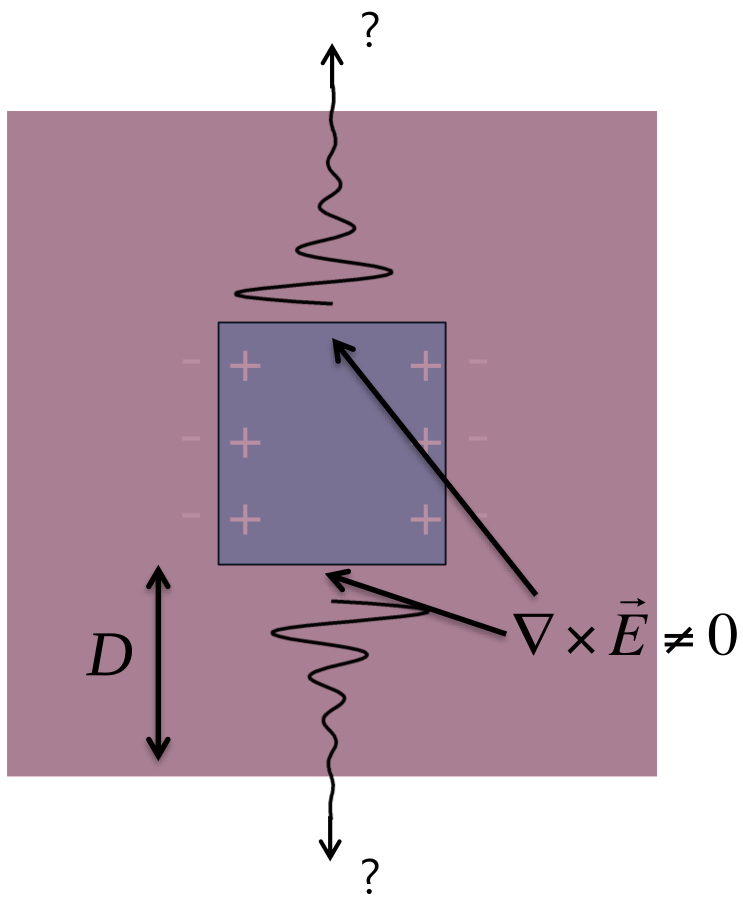
Two-dimensional PIC simulation



Inside the Plasma (Probe1)

In vacuum region (Probe2)

PDO embedded in a Homogeneous Plasma



A misleading concept:

When $D < \delta$, the radiation is emitted with reduced amplitude.

Note: δ is the skin depth.

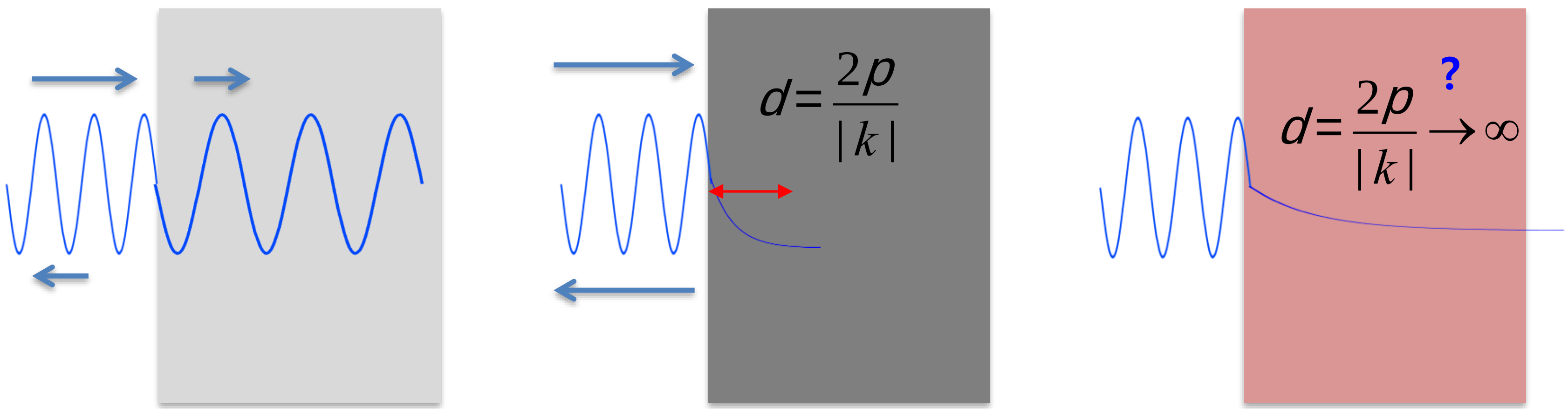
Skin Depth at Cut-off

Dispersion relation of an electromagnetic wave in plasma $\omega^2 = \omega_p^2 + c^2k^2$

Underdense: $\omega > \omega_p \propto \sqrt{n}$, k is real

Overcritical: $\omega < \omega_p \propto \sqrt{n}$, k is pure imaginary

Cut-off: $\omega = \omega_p, k = 0$



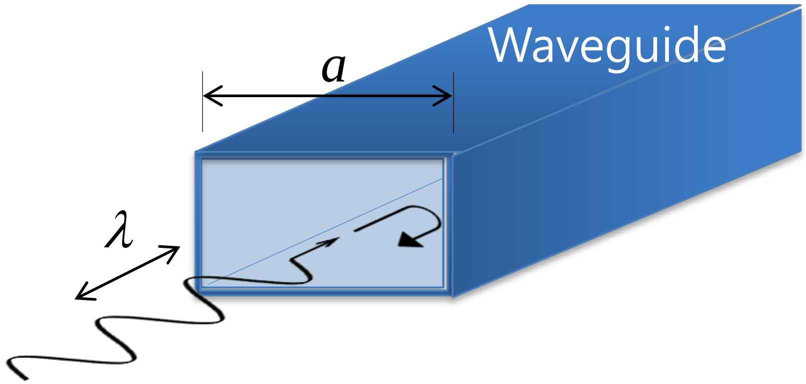
Underdense Overcritical Cut-off

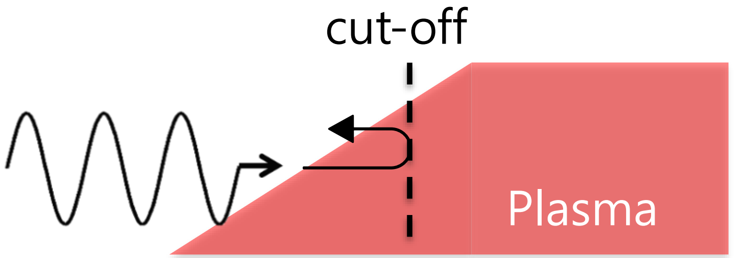
At cut-off, there is no stationary state!

Cut-off in Plasma-like Media

Waveguide

Plasma

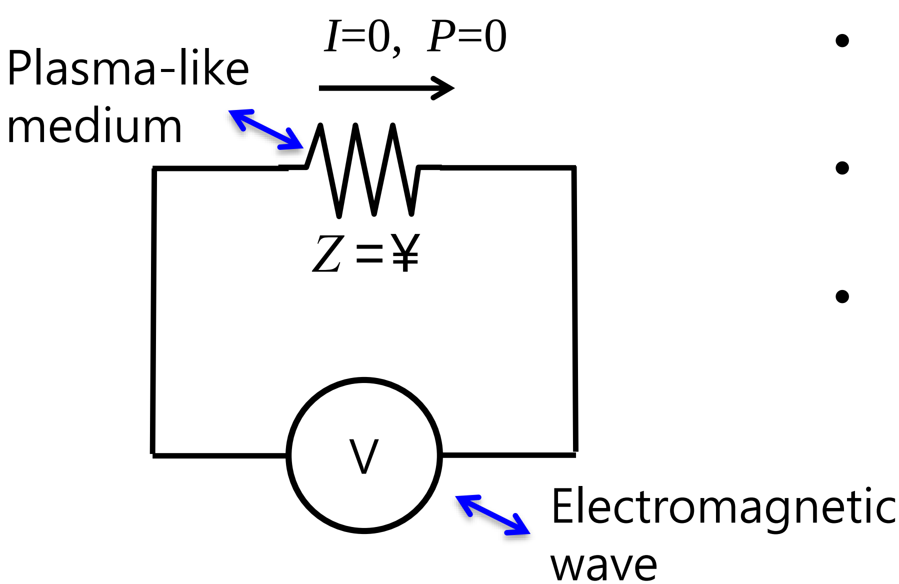




At the cut-off point, the propagation of the electromagnetic wave is ‘cut off’.

Classical View of Cut-off

Equivalent Circuit

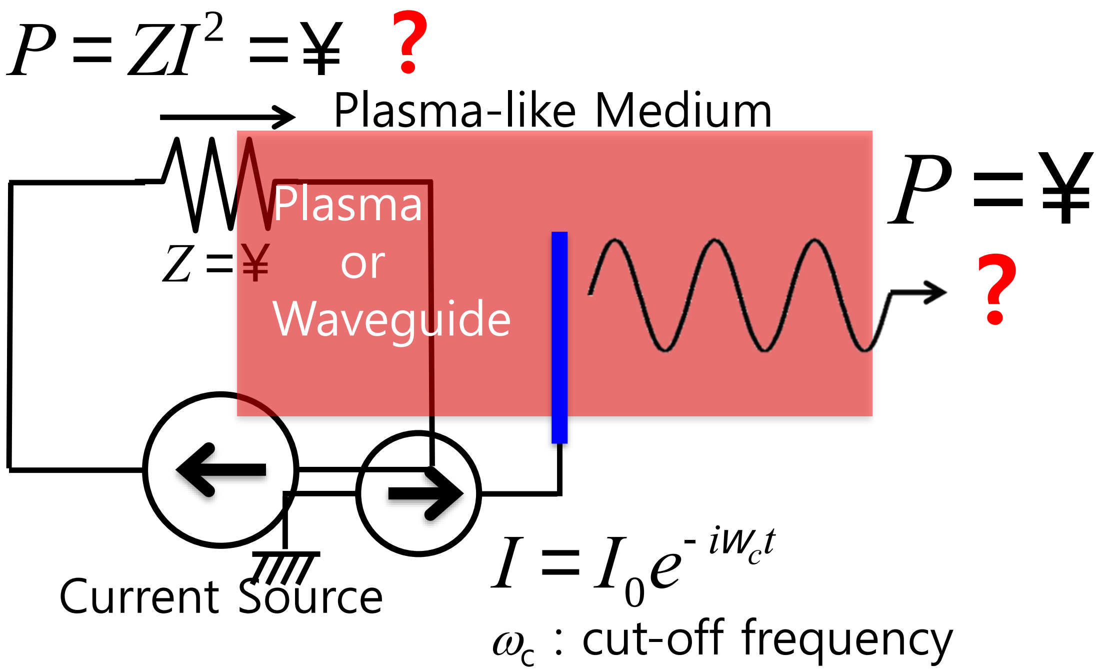


- From Faraday's law $\vec{k} \times \vec{E} = \omega \vec{B}$
- k=0 leads to B=H=0
- The radiation impedance is infinite

$$Z = \frac{E}{H} \rightarrow \infty$$

Classically, the cut-off means the stopping of the power transmission!

Current Source & Cut-off



- No steady state mode available.
- Dynamic equation should be examined to find the behavior of the electric field.

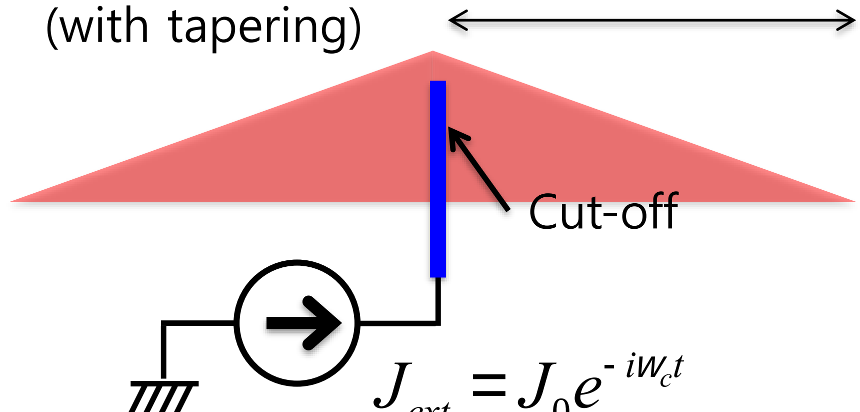
Driven Schroedinger Equation (DSE)

Start from the Wave Equation
with an external current source

$$\frac{\partial^2 E_\perp}{\partial z^2} - \frac{\partial^2 E_\perp}{\partial t^2} = S_\perp + \frac{\partial J_{ext}}{\partial t}$$

Plasma or Waveguide
(with tapering)

L



$$J_{ext} = J_0 e^{-i\omega_c t}$$

Current source $\quad \dfrac{\partial J_{ext}}{\partial t} = -iJ_0 \delta(z) e^{-i\omega_c t}$

Envelope Decomposition $\quad E_\perp = \hat{E}(z,t) e^{-i\omega_c t}$

Driven, Time-dependent Schroedinger Equation

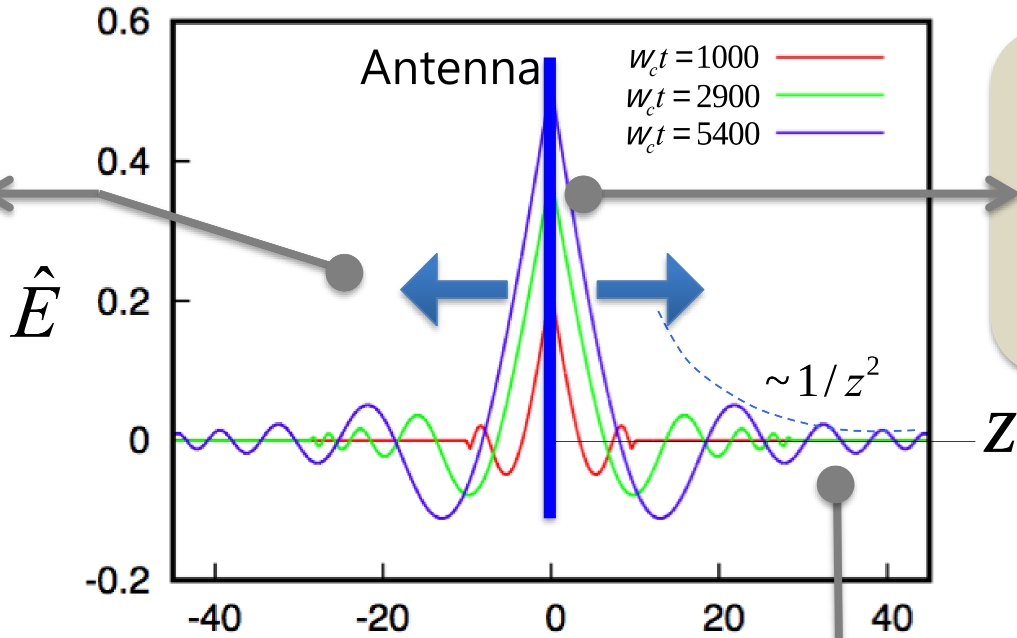
$$\frac{\partial^2 \hat{E}}{\partial z^2} + 2i \frac{\partial \hat{E}}{\partial t} + \frac{z}{L} \hat{E} = -iJ_0 \delta(z)$$

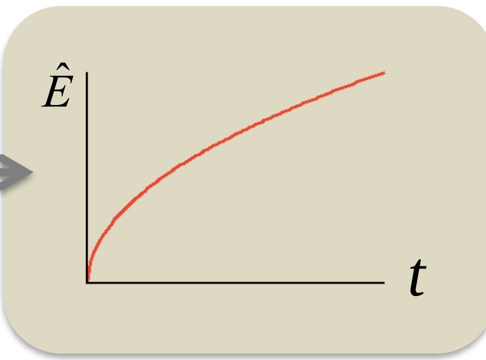
Temporally-growing, spatially diffusing field

For $z » 0$ $\hat{E}(z » 0, t) = \frac{J_0}{2\sqrt{p}}(i - 1)\sqrt{t}$

Diffusing speed

$$v = \frac{c}{2}\sqrt{\frac{p}{2w_c t}} \mu \frac{1}{\sqrt{t}}$$



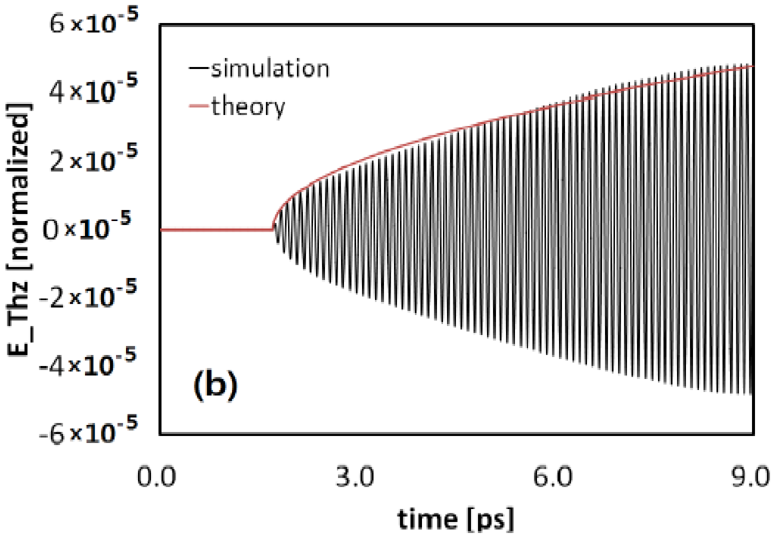


$k = \frac{z}{t}$ Wavenumber is self-similar

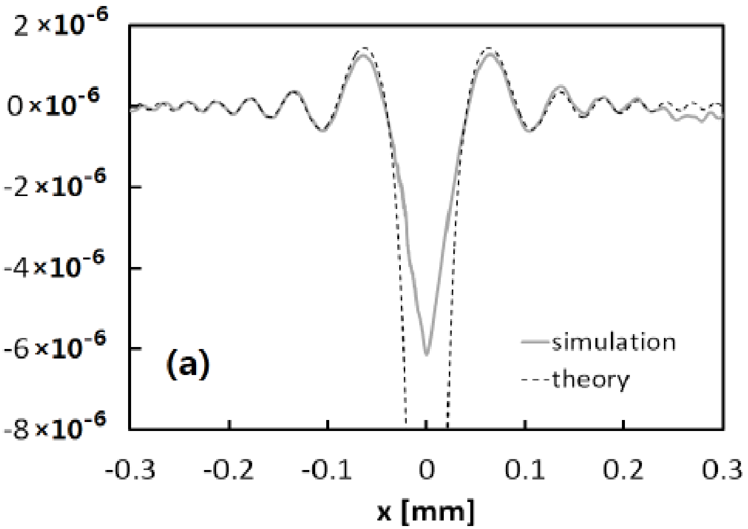
For $\frac{z^2}{t} >> 1$ $\hat{E}(z, t) = -\frac{J_0}{\sqrt{2p}} \frac{t^{3/2}}{z^2} \exp\left[i\left(\frac{z^2}{2t} + \frac{p}{4}\right)\right]$

DSE and Full-wave Solutions

Temporal growth of the Electric field at z=0



Electric field vs. z



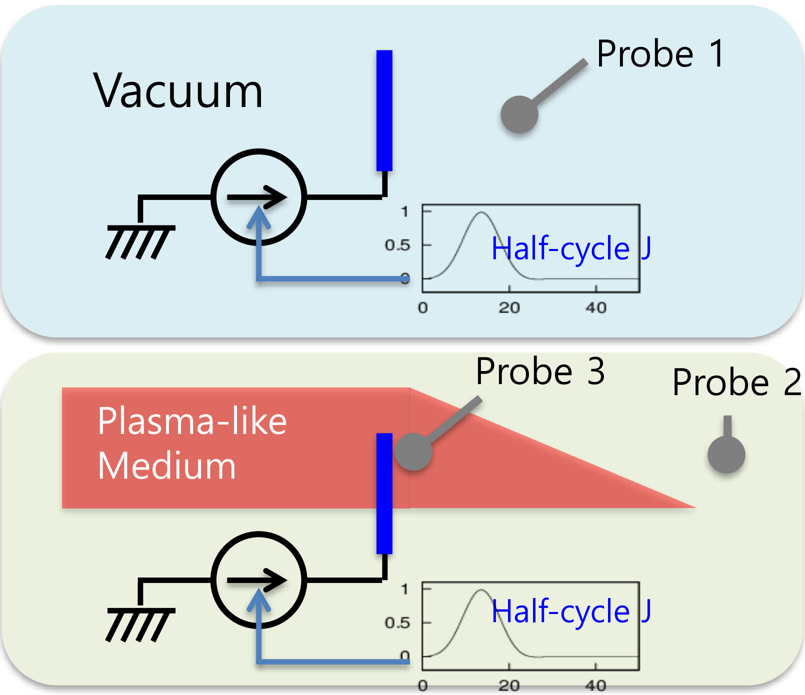
Analytic solution of DSE coincides well with the numerical solution of the full wave equation.

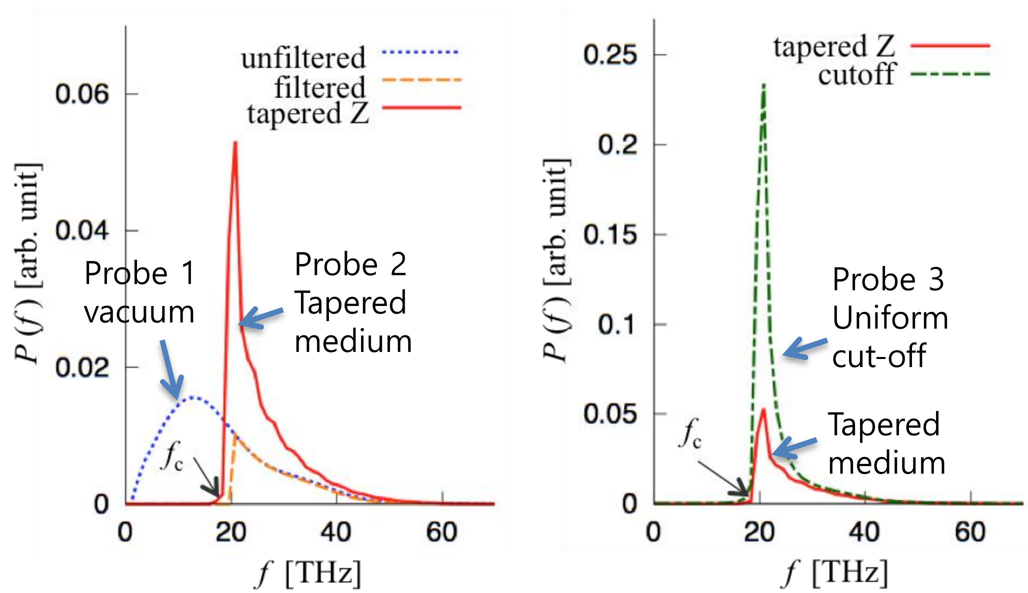
Paradox of Infinite Power Resolved

The infinite Power of radiation in steady state occurs as a spatially-diffusing and *temporally-growing* radiation!

Selectively Enhanced Emission (SEE)

Numerically Solved the Wave Equation in 2D





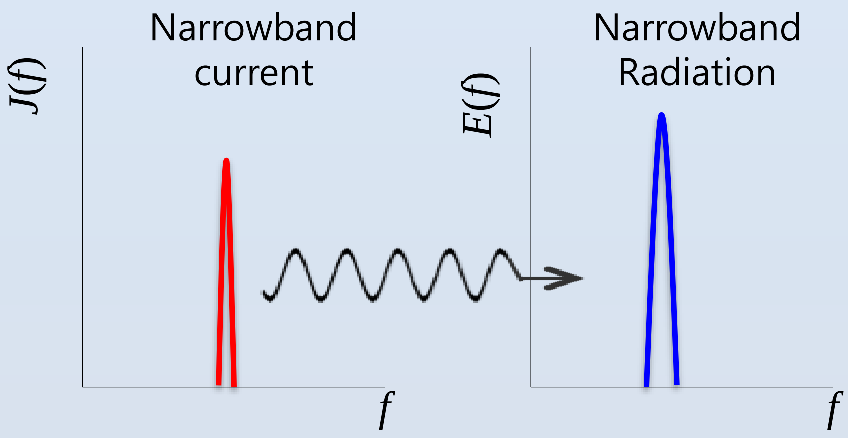
- Spectral density at the cut-off frequency is selectively enhanced by an order of magnitude.

'Selectively Enhanced Emission (SEE)'

Hur et al., Sci. Rep. 7:40034 (2017)

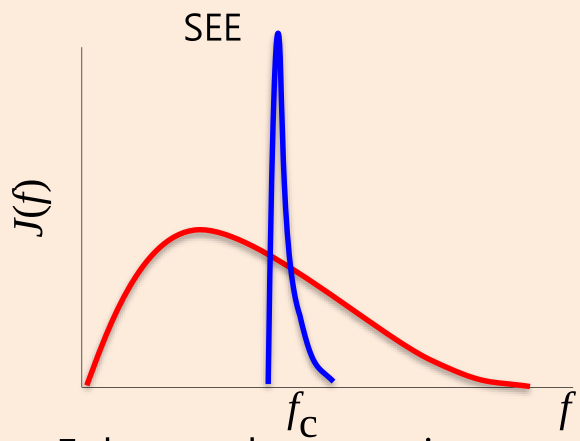
A New Way of Thinking Radiation Sources

Common sense



Requires a finely-tuned wave-particle structure
e.g.) beam-undulator

New concept



Enhance the pumping at a desired frequency by increased Impedance

Practical Impact

- Easy conversion of a broadband radiation source to a narrowband one enables flexible use of a given broadband radiation source

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Multi-Dimensional Solutions

Asymptotic field solution for each dimension

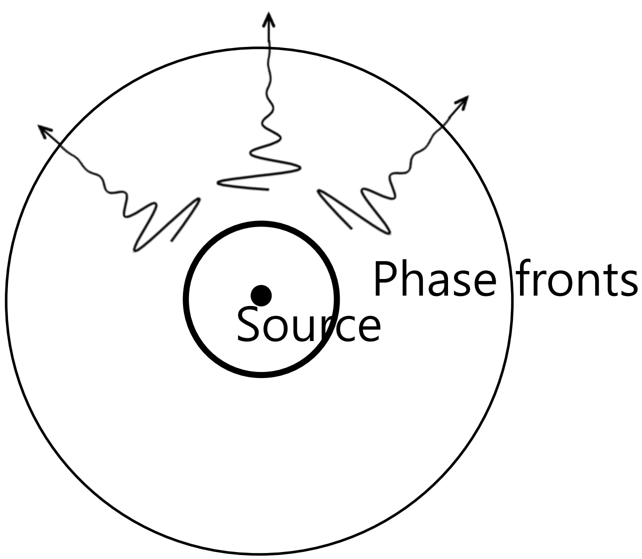
$$E_{1D}(z,t) = -\frac{J_0}{\sqrt{2\pi}}\frac{t^{3/2}}{z^2}\,\mathrm{Re}\exp\left[i\left(\frac{z^2}{2t}+\frac{\pi}{4}-t\right)\right]$$

$$E_{2D}(z,t) = -\frac{J_0}{\sqrt{2\pi}}\frac{t^{3/2}}{z^{5/2}}\,\mathrm{Re}\exp\left[i\left(\frac{z^2}{2t}+\frac{\pi}{4}-t\right)\right]$$

$$E_{3D}(z,t) = -\frac{J_0}{\sqrt{2\pi}}\frac{t^{3/2}}{z^3}\,\mathrm{Re}\exp\left[i\left(\frac{z^2}{2t}+\frac{\pi}{4}-t\right)\right]$$

Decay of phase front

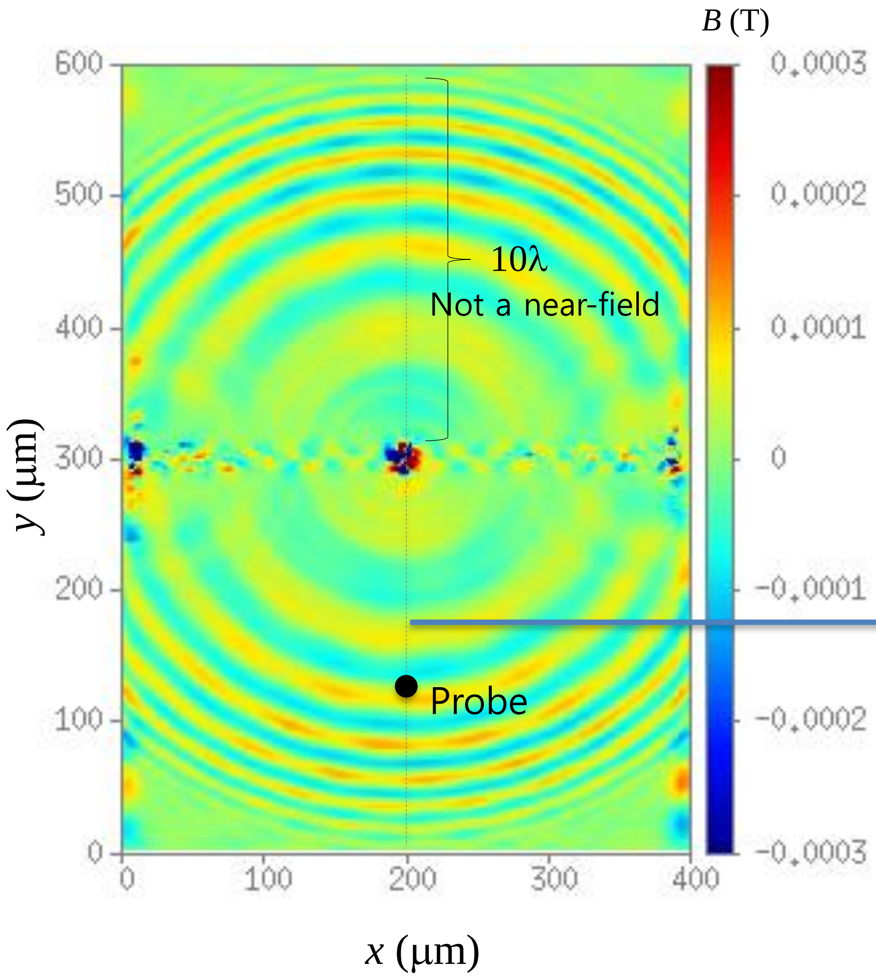
Diffusing-growing field at cut-off	Propagating far-field in a transparent medium
$E_{1D} \propto \frac{1}{\sqrt{z}}$	$E_{1D} \propto const.$
$E_{2D} \propto \frac{1}{z}$	$E_{2D} \propto \frac{1}{\sqrt{z}}$
$E_{3D} \propto \frac{1}{z^{3/2}}$	$E_{3D} \propto \frac{1}{z}$

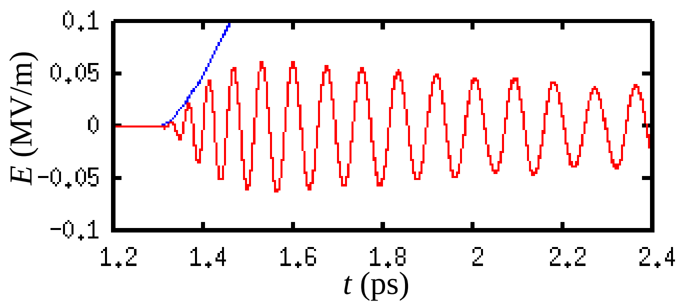


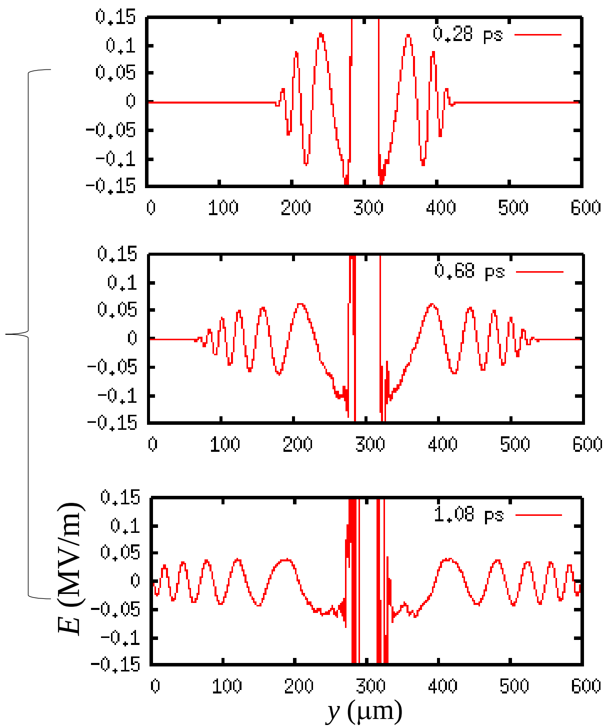
- A given phase front decays faster than regular propa gating fields. However,
- Following phase fronts have larger and larger amplit ude.
- When the source is an energy reservoir, field energy can be delivered over an arbitrarily large distance.
- Initial source energy determines the distance of the f ield energy transport.

Field Transport in a Homogeneous Plasma

2D PIC Simulation







Frequency Drift

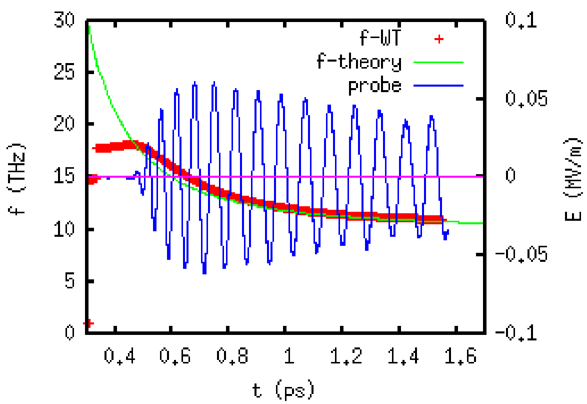
From oscillation phase, $\varphi = \dfrac{\zeta^2}{2\tau} + \dfrac{\pi}{4} - \tau$

$$\omega = -\frac{\partial \varphi}{\partial \tau} = \frac{\zeta^2}{2\tau^2} + 1$$ Time-dependent Frequency

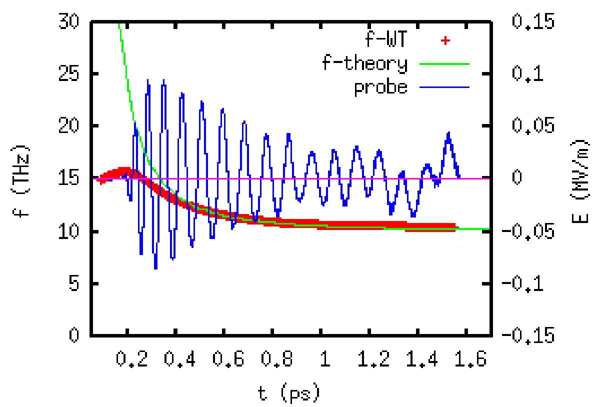
$$k = \frac{\partial \varphi}{\partial \zeta} = \frac{\zeta}{\tau}$$ Self-similar Wavenumber

- The 1st phase front propagates roughly with c. Then at a given position z, the frequency of the 1st-arriving signal is $1.5\omega_p$.
- Then the frequency drifts asymptotically toward ω_p.

From wavelet transformation of the chirped signal,



180 μm from the source

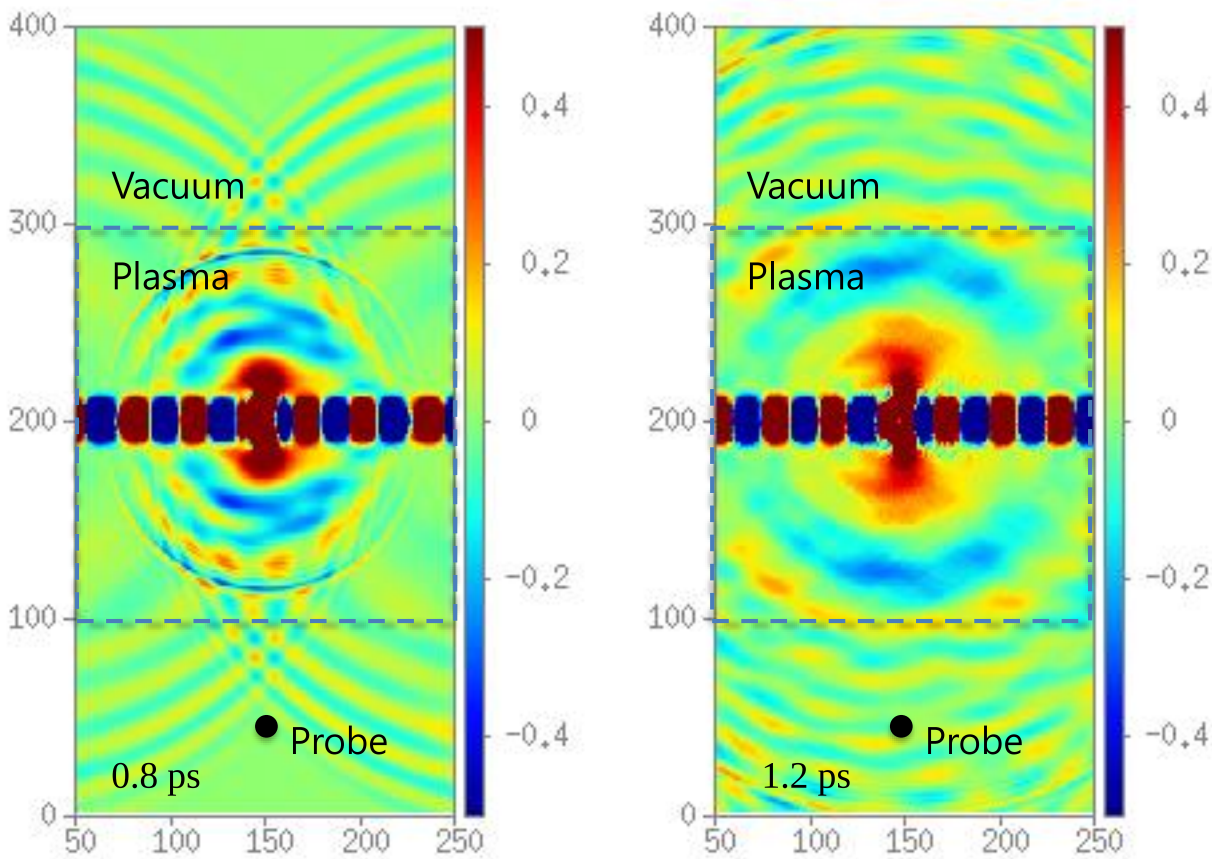


100 μm from the source

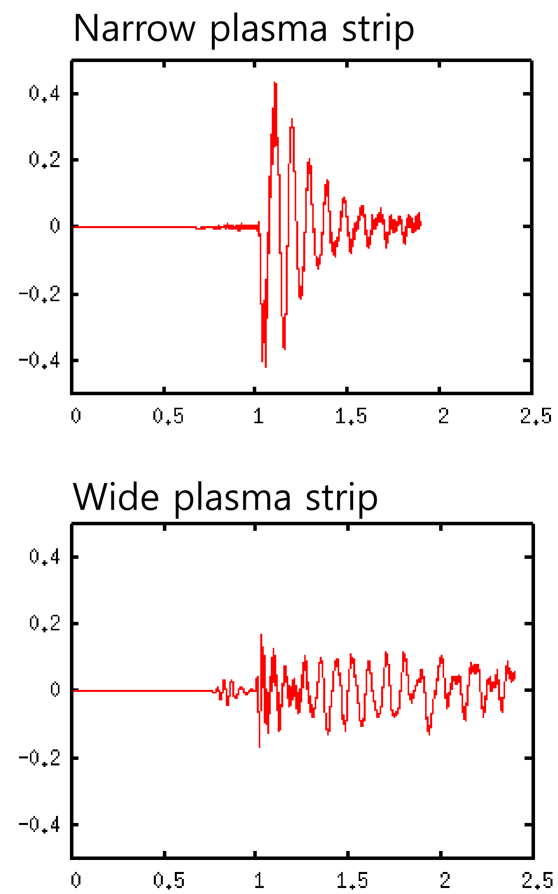
An observer sees frequency different from ω_p, while the source oscillates monochromatically at ω_p only!

Radiation from Locally Homogeneous Plasmas

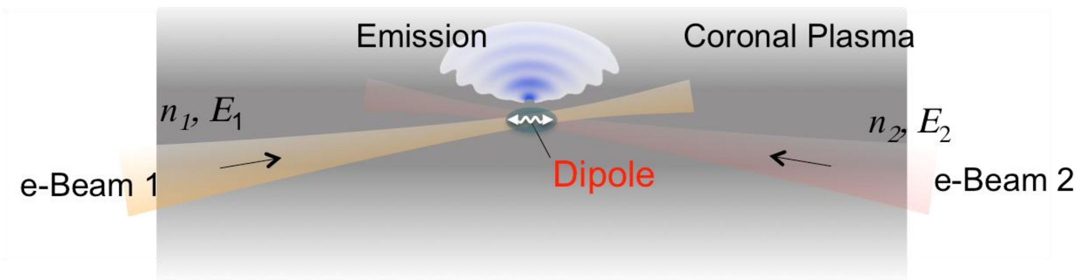
2D PIC Demonstration

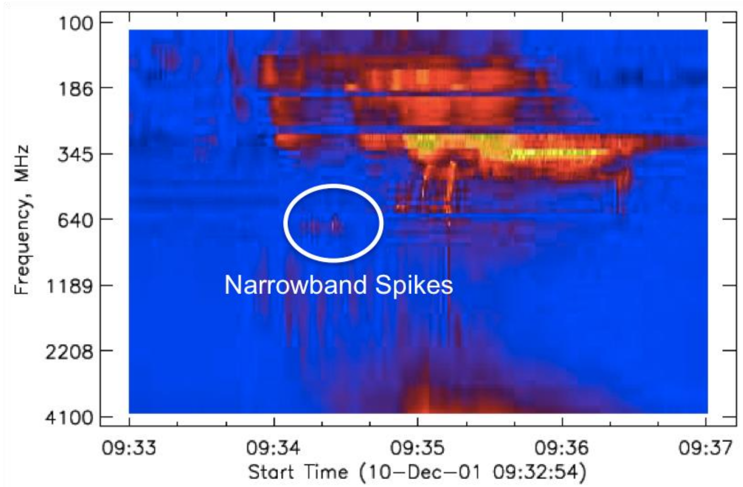


Signal at the Probe



A New mechanism of the radio-burst from space





Colliding-beams to build-up dipole field
To explain the Narrowband Spike

Thank You!

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2009