The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

310/1749-46

ICTP-COST-USNSWP-CAWSES-INAF-INFN
International Advanced School
on
Space Weather
2-19 May 2006

Plasma Waves Interaction

Cesidio BIANCHI
Istituto Nazionale di Geofisica e Vulcanologia
Dipartimento di Aeronomia
Via di Vigna Murata 605
00143 Rome
ITALY

Vertical ionospheric sounding: a technique to measure the electronic density in the ionosphere.

Electromagnetic waves – plasma interaction

Cesidio Bianchi INGV - Roma Italy

$$k \longrightarrow n$$

By using the relation of dispersion we see the phenomena from a point of view of the electromagnetic wave.

From another point of view (medium), the representative quantities are the refractive index, dielectric permittivity etc.. The relation between the refractive index n and the propagation vector k is:

$$k = n\,\omega/c$$

or in term of relative dielectric permittivity we can write

$$k = \sqrt{\varepsilon_r}\,\omega/c$$

Refractive index

Permittivity is the property of a dielectric medium that determines the degree in which it modifies an electric field. Permeability is the property of a magnetisable medium that determines the degree in which it modifies the magnetic flux in the region occupied by it in a magnetic field. (We do not assign magnetic properties to the ionospheric plasma but the plasma is immersed in the terrestrial magnetic field)

The ionospheric plasma is a rather complex medium because the magnetic field which gives non isotropic properties to the medium (double sign in the Appleton- Hartree eq.).

The collisions between electrons and neutral particles make the refractive index complex.

The restoring elastic force is due to the heavy ions.

Magnetoionic theory

Starting from the constitutive equation of the medium (the ionospheric plasma) we can write the equation of Appleton – Hartree for refractive index

$$n^2 = 1 - \frac{X}{1 - jZ - \frac{Y_T^{\ 2}}{2(1-X-jZ)} \pm \sqrt{\frac{Y_T^{\ 4}}{(1-X-jZ)^2} + Y_L^{\ 2}}}$$

This subject brings back to the *Magnetoionic Theory* In the above equation appear three physical quantity hidden in *X*, *Y* and *Z*.

$X = f_p^{\ 2} / f^{\ 2}$ $\quad$ $Y = f_B / f$ $\quad$ $Z = \nu / f$

fp, *fB*, ν

- the plasma frequency *fp* is:

$$f_p = \frac{1}{2\pi}\sqrt{\frac{Ne^2}{m\varepsilon_0}}$$

-The frequency of collision between electrons and neutral molecules (ν) is:

$$\nu = 1/\tau$$

being τ is the average time between collisions

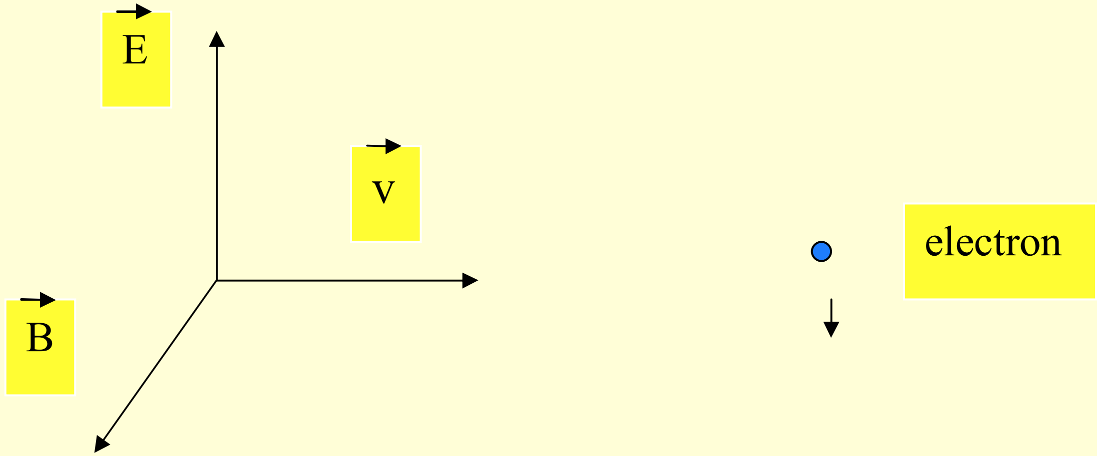
-frequency of cyclotron (f_B)

$$f_B = e B / m 2\pi$$

establishes the condition of propagation of the wave through the magnetised ionospheric plasma.

Lorentz's force

The electric charges under the field's action of the a TEM wave, move in direction of the electric field **E** while the magnetic field **B** later acts only on the moving charges.



- On the q charge the Lorentz force ***F*** given by:

$$\mathbf{F} = q\mathbf{E} + q\mathbf{V} \times \mathbf{B}$$

- Also the mass of the charge (that not appear in the formulas) is very important. Heavy charges have a tendency   to remain in a fixed position in any case they move slower than light charges especially if the oscillation of the electric field E is high. This leads to the properties: polarization of the plasma.

Radiation pressure

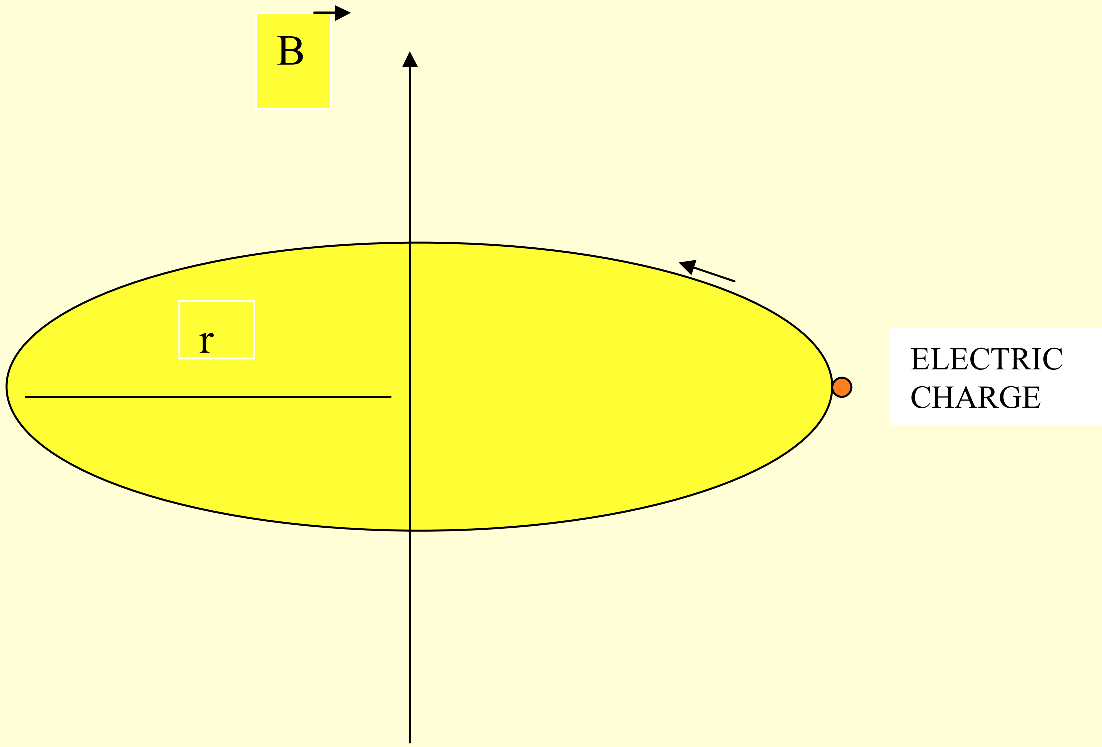
-The magnetic field ***B*** of the e.m. transfers only the momentum.
It means that the charges move in the direction of propagation. Hence the amount of charges plasma is under the pressure of the radiation in the direction of the wave propagation.

In practice this effect is negligible. Hence, the magnetic component of the e.m wave does not interact with the plasma.

On the contrary the terrestrial magnetic field confers to the plasma special properties that are the subject of the magnetoionic theory.

GYRO-FREQUENCY ω_B

In a static magnetic field **B** the moving charges follow spiral trajectory along the field's lines. The projection in a transversal plane is circular orbits.



If m is the mass of the charge (q) and r the radius, the magnetic force is balanced with centrifugal force:

$$mV^2/r = qVB$$

$$mV^2/\omega_B V = qVB$$

where, $r = \omega_B V$.

Combining the two equations we obtain:

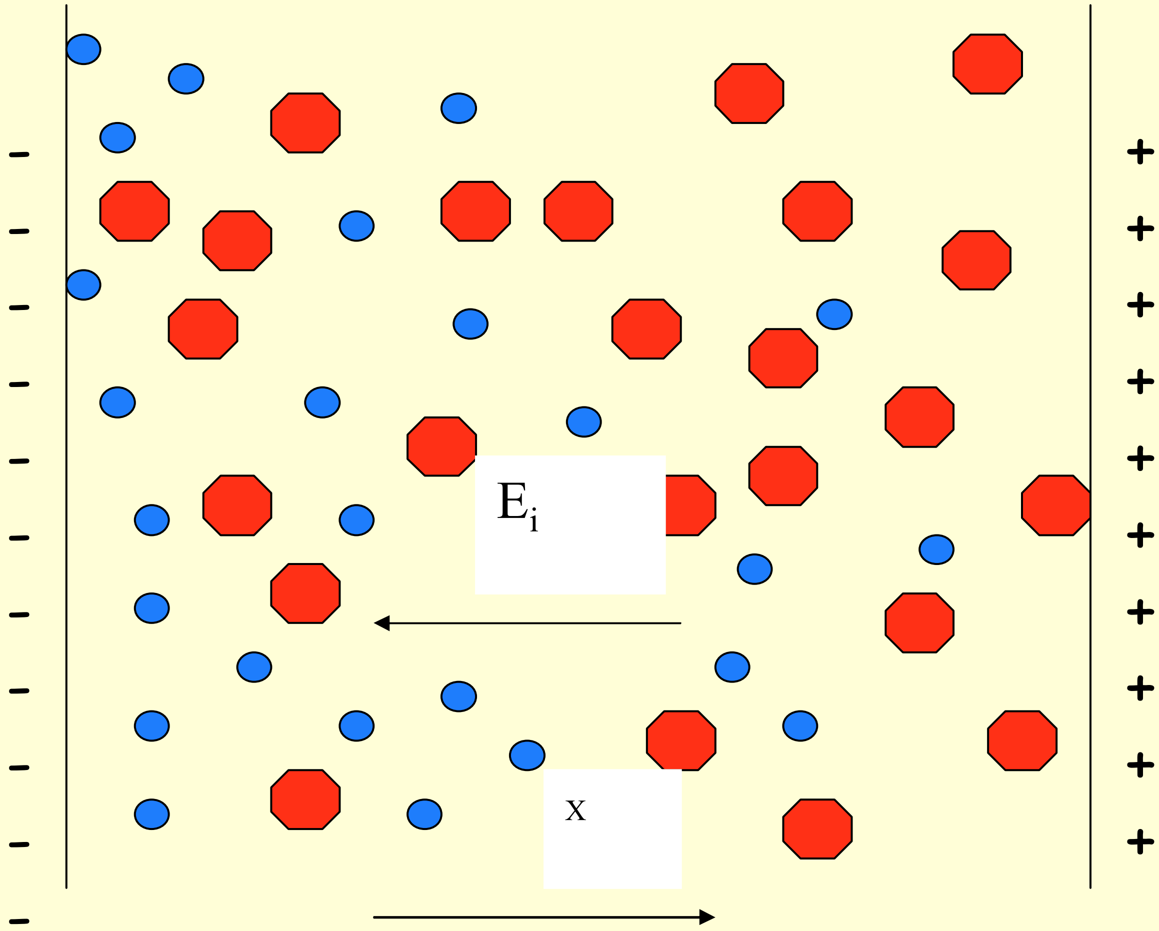
$$\omega_B = eB/m \quad \text{(rad/s)}$$

$$f_B = \omega_B/2\pi = eB/\ 2\pi\, m \quad \text{(Hz)}$$

Electronic gyro-frequency in thermosphere is 1.2 MHz while ionic gyro-frequency is about 50 Hz.

PLASMA FREQUENCY ω_p

- When free charges of opposite signs that constitute not-collisional plasma (blue ones are negative and red one are positive) undergo to the excitation of an external electric field E_e, create a double layer and consequently an internal electric field E_i.



This internal electric field is: $E=\sigma/\varepsilon_o$, where, σ is the surface density of the charge and ε_o is dielectric permittivity of the vacuum.

- The surface density will be:
  - $\sigma = Nex$
- The internal electric field established inside the considered volume of plasma is: $E_i = Nex/\varepsilon_o$. Therefore, the force F acting on the single electron is given by:
  - $F = -N e^2 x/\varepsilon_o$.
- F is a restoring force that retrieves the electrons that obey the harmonic equation:
  - $m\, d^2x/dt^2 = -N e^2 x/\varepsilon_o$

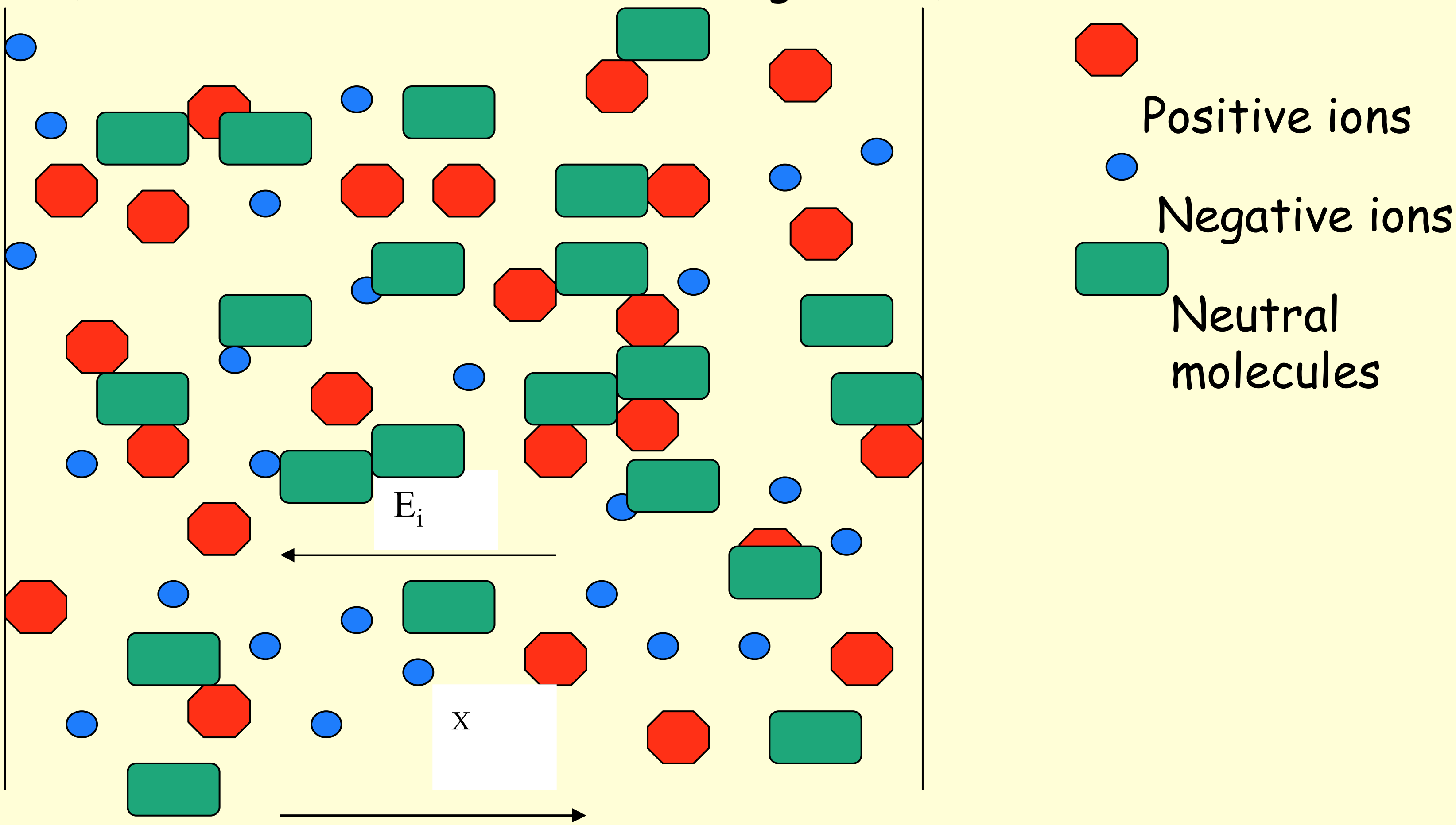
The electrons vibrate with respect to the equilibrium position at the angular frequency ω_p given by:

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

- This quantity determines the condition of the wave propagation through the plasma. In fact:
- - if the angular frequency (say ω) of the incident wave is greater than ω_p the wave will propagate through the plasma
- if the angular frequency ω of the incident wave is lower than ω_p the wave will be reflected by the plasma

Frequency of collision

In the ionospheric plasma the electrons collide mainly with neutral molecules (electron-ion collision can be neglected).



The above figure is a rough representation of collisional cold plasma .

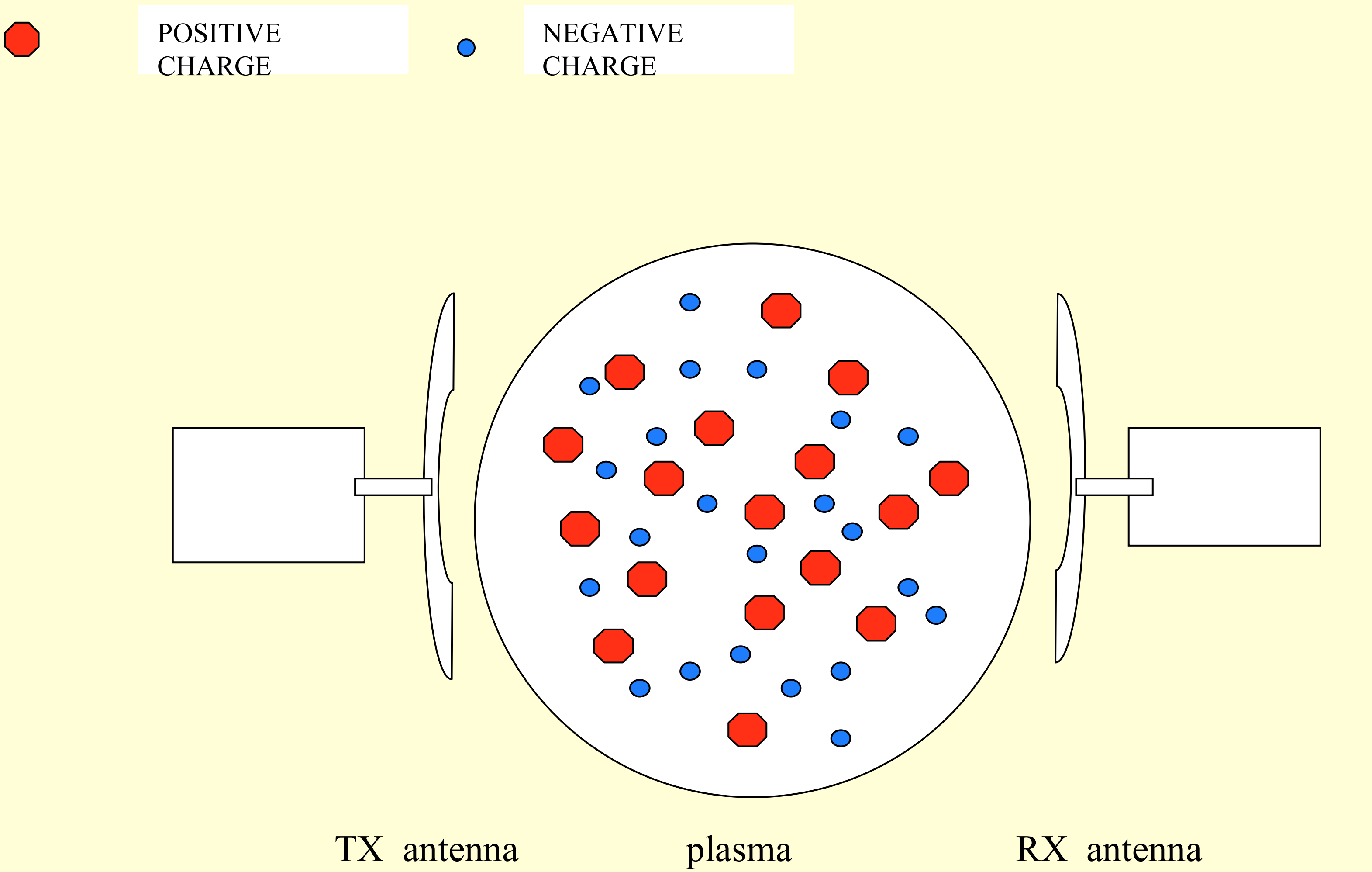
Frequency of collision cond.

- If the time between the collisions is τ (in the average) the collision frequency ν will be: $\nu=1/\tau$. The electrons, (in a macroscopic point of view) undergo a force that is proportional to the collision ν as in the following relation:

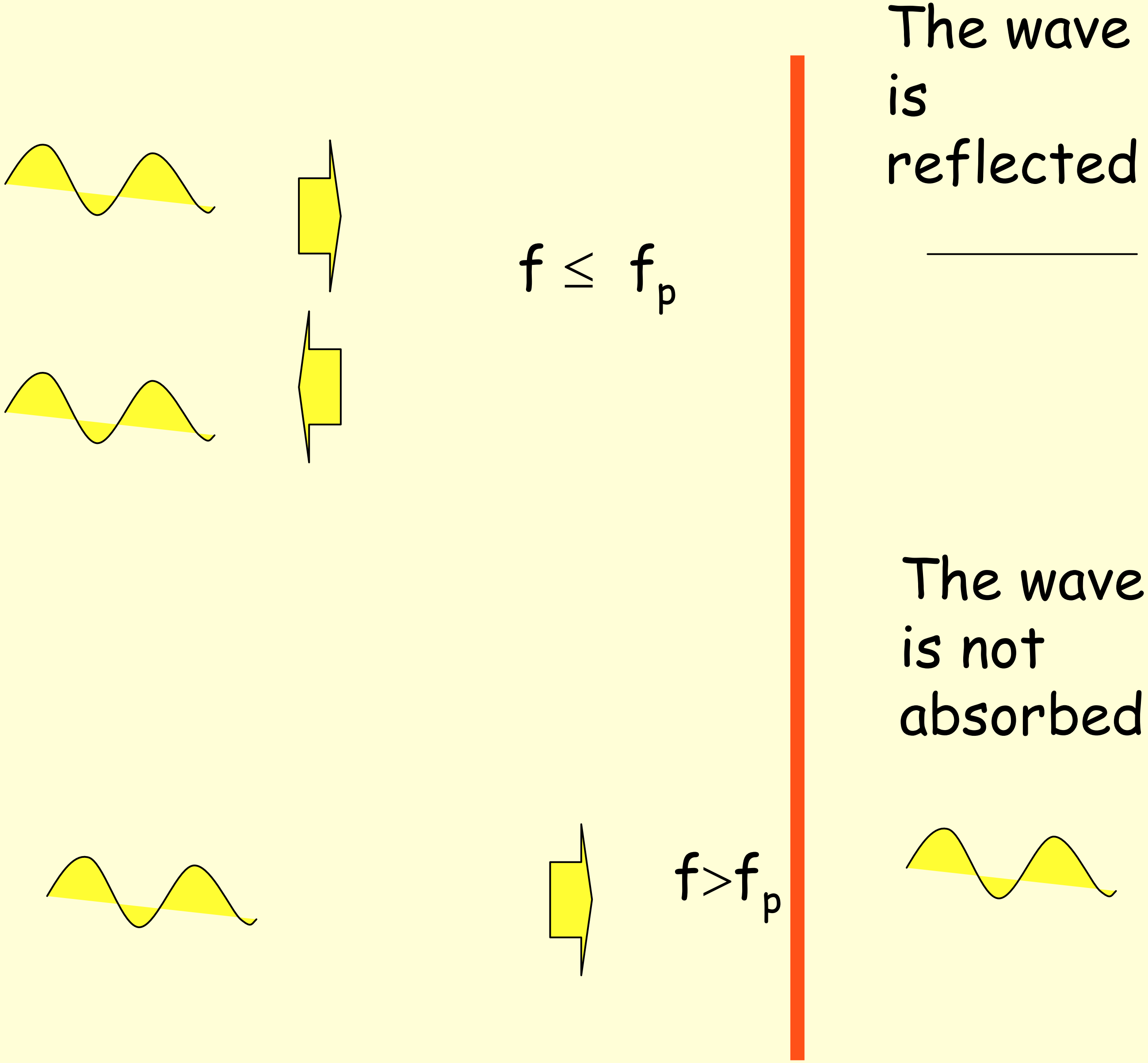
$$F = m \nu V$$

- We can state that the electric field gives motion to the electrons of the plasma that are braked by the frictional force due to the collisions. Therefore, the e.m. wave is absorbed by the neutral molecules of the plasma.

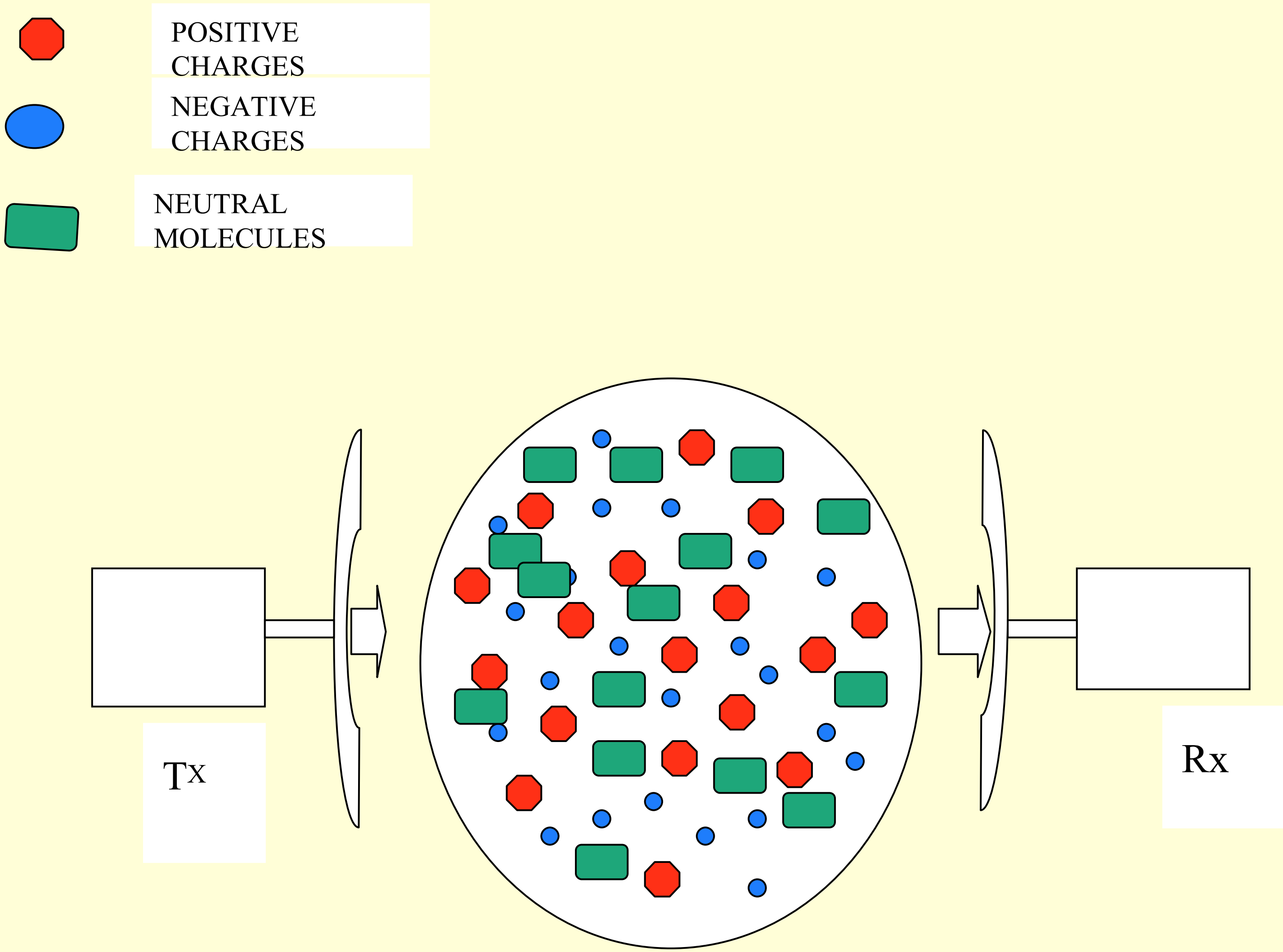
Thought experiment 1



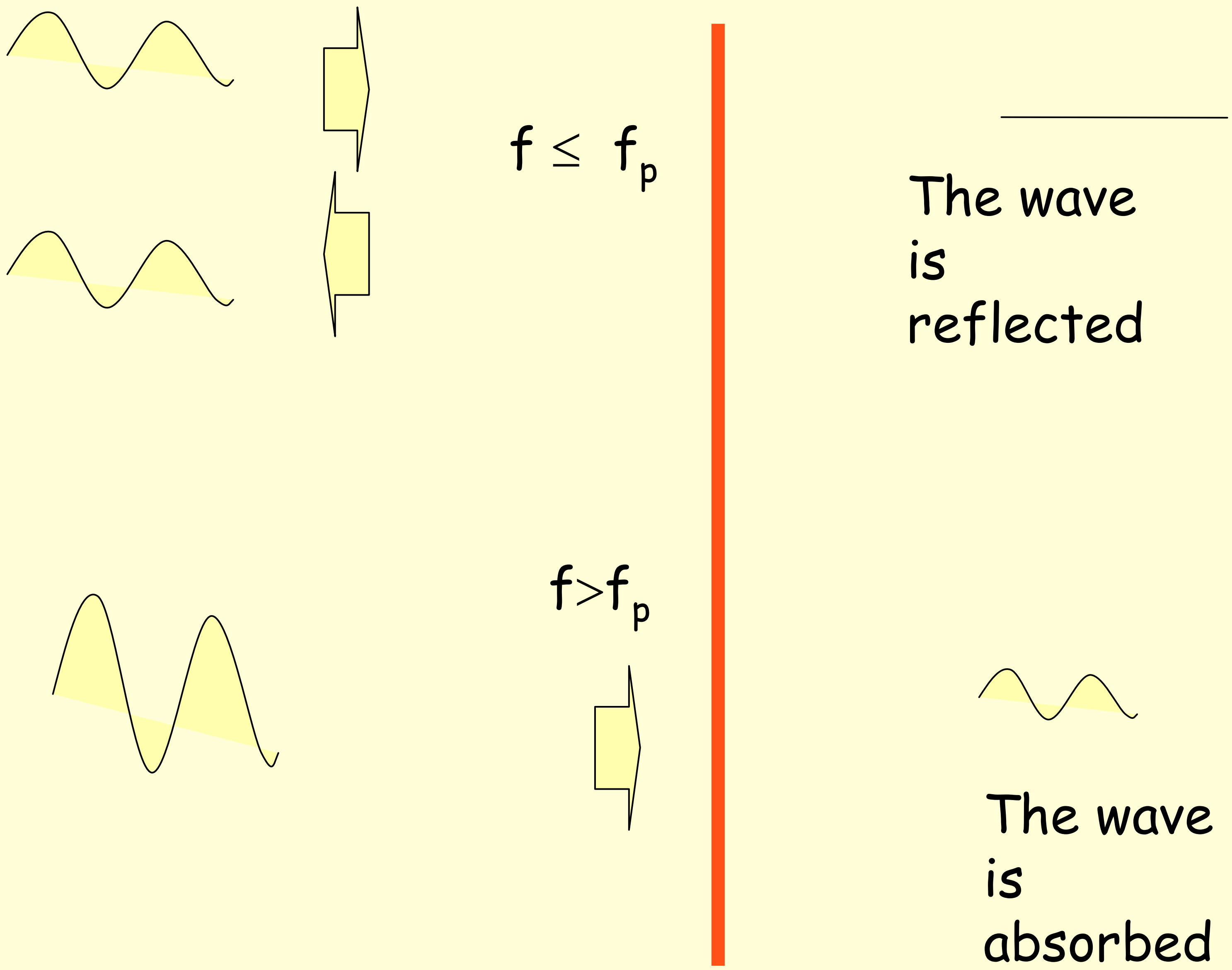
reflection



Thought experiment 2

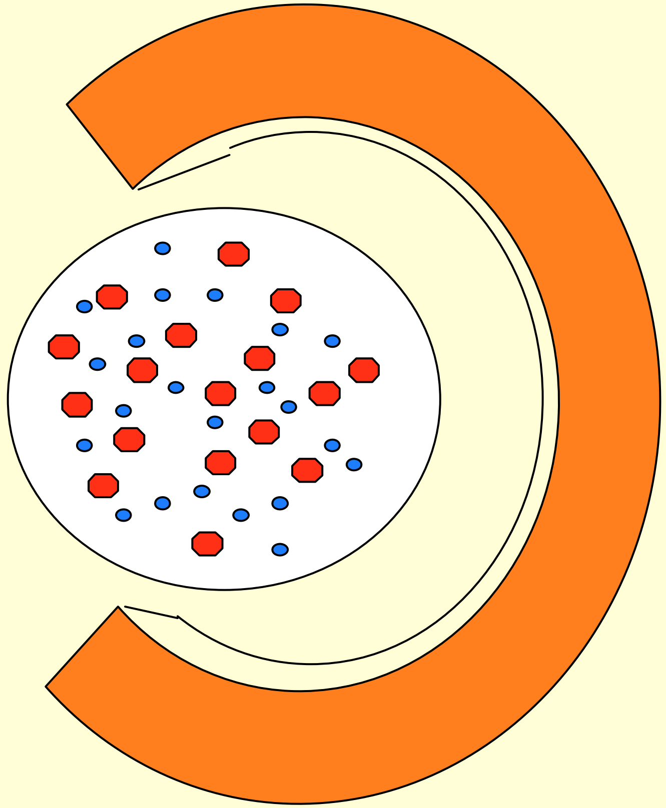


reflection



MAGNETO PLASMA

PLASMA IN
A STATIC
MAGNETIC
FIELD



CRITICAL FREQUENCY IN THE MAGNETO-PLASMA

THE TERRESTRIAL MAGNETIC FIELD GIVES BI-REFRACTIVE PROPERTIES TO THE PLASMA

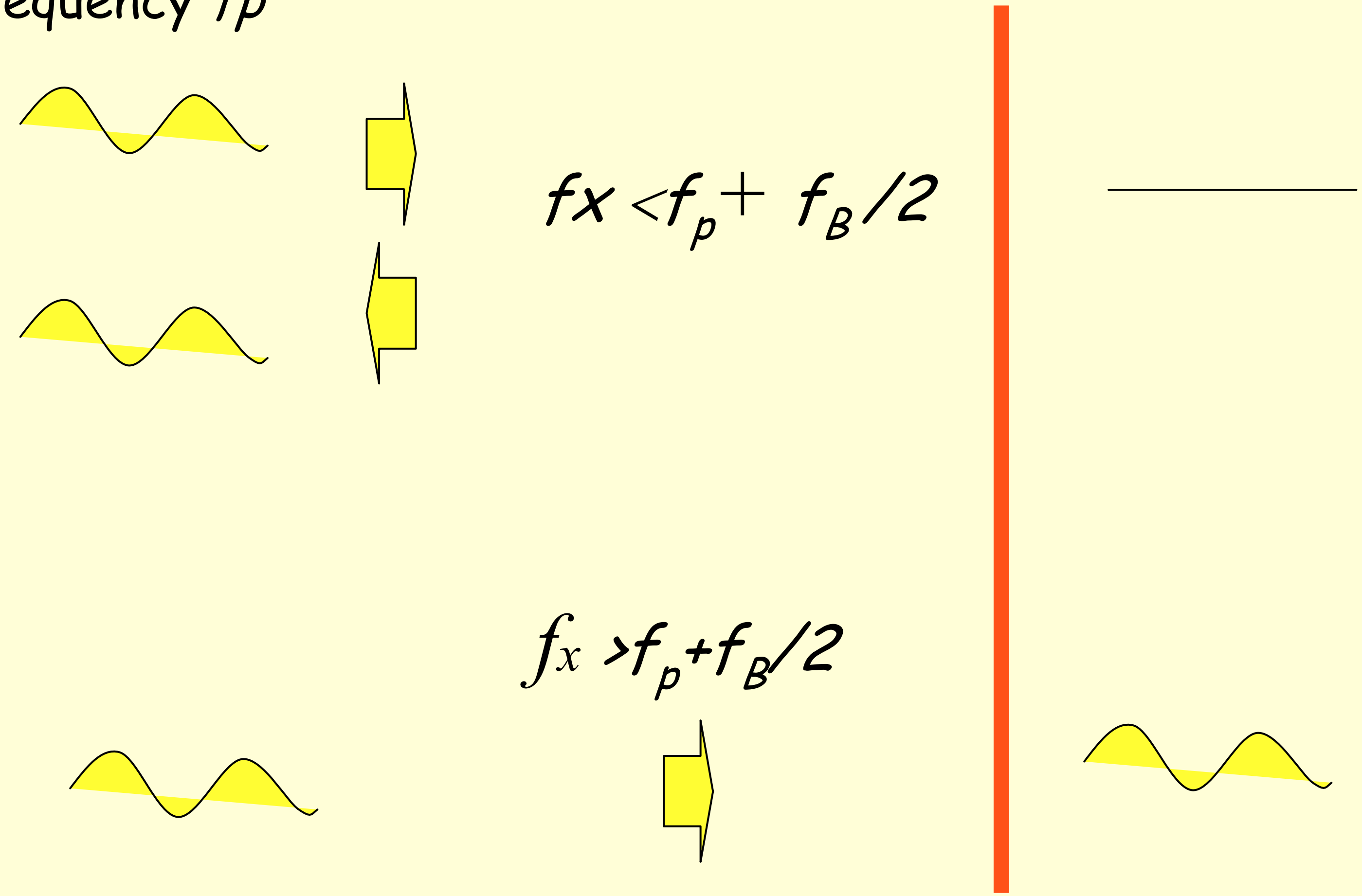
AN E. M. WAVE THAT PROPAGATE THROUGH A MAGNETO-PLASMA IS DIVIDED INTO TWO COMPONENTS CALLED "MAGNETO-IONIC", THE TWO COMPONENTS WILL PROPAGATE SEPARATELY LIKE TWO DIFFERENT WAVES.

- THE FIRST ONE IS NOT INFLUNCED BY THE MAGNETIC FIELD (PREOVIOS CASE).

- THE SECOND ONE IS INFLUNCED BY THE MAGNETIC FIELD AND WILL BE REFLECTED AS FOLLOWING:

Extraordinary component

The extraordinary component reflects at the frequency greater than the plasma frequency *fp*

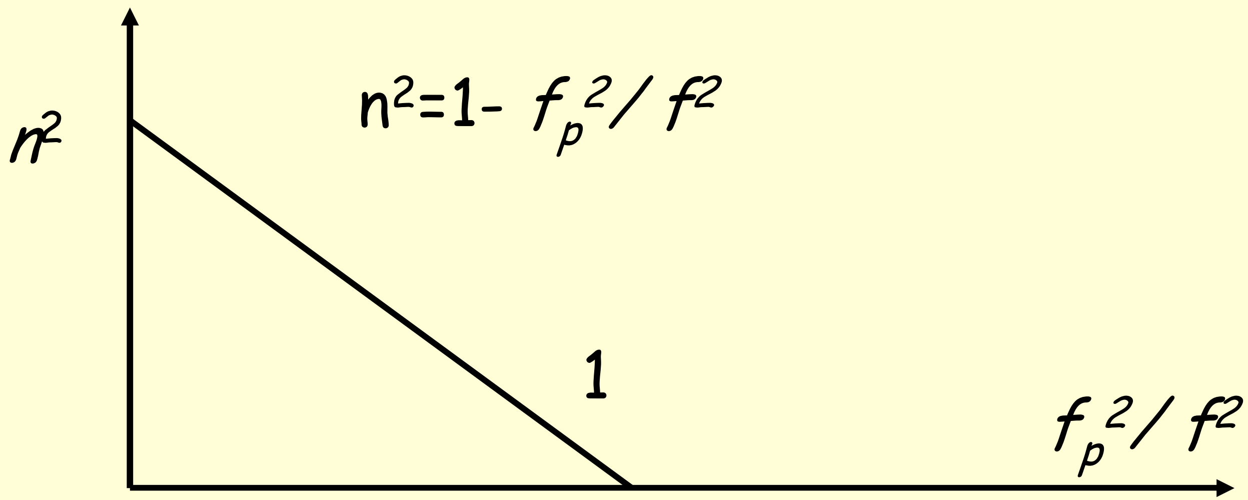


$$fx < f_p + f_B/2$$

$$f_x > f_p + f_B/2$$

The extraordinary component propagate when the above relation is valid

Simple dispersion relation in non- magnetized non-collisional plasma



Refractive index *n* is real assuming value between 1 and 0

collisional plasma - dispersion relation in non magnetized plasma

$$n^2 = 1 - \frac{X}{1 - jZ}$$

Refractive index *n* is complex and always assumes values greater than 0.

The imaginary part of the refractive index n_i is proportional to $N\,\nu/\omega^2$