RF Physics and Applications

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30 Years of Aditya Tokamak

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Introduction

- RF covers a very wide ground in terms of frequency.

- In general, one can state that starting from a few MHz or even little lower to right up to microwave frequencies may be treated as RF.

- But an important question that arises is how does RF, as we understand it conventionally, differ from low frequency AC voltages and currents and behave the way it does or in essence, what truly distinguishes RF signals from low frequency signals?

- In this talk we shall try to identify some of the basic attributes of RF.

- One may take it as a law of nature that whenever a disturbance is created locally, it tries to propagate out in the medium surrounding it or whatever channel is accessible to it.

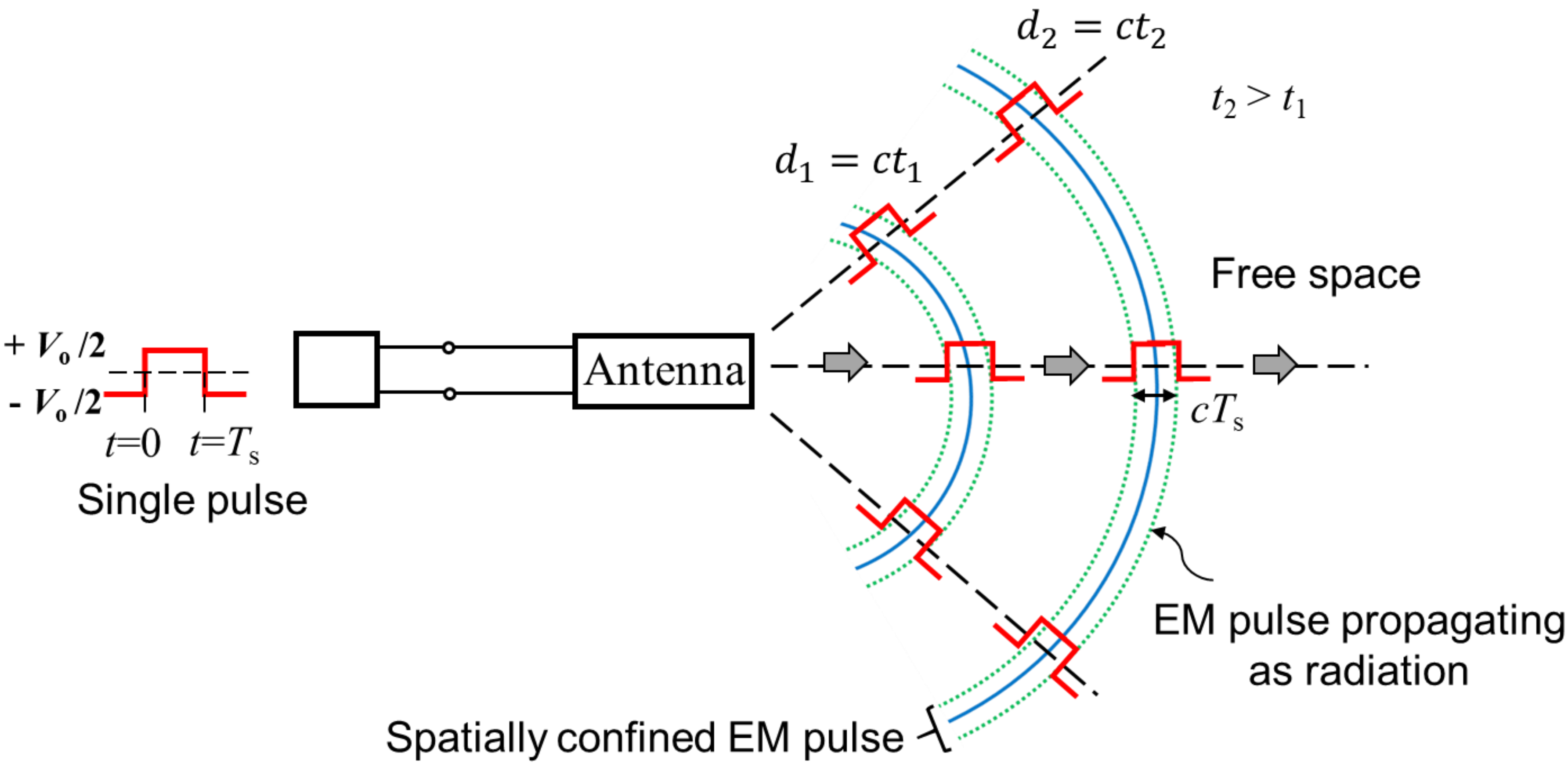
- The physical mechanism by which coupling to the adjoining medium takes place depends both on the disturbance and the medium.

- It is also a law of nature that all disturbances may propagate at finite speeds only.

- Thus the time delay in getting to a point remote from the origin of the disturbance is a key feature of all disturbances.

- In this talk we shall confine ourselves to RF disturbances only.

EM pulse propagation in free space



It may be noted that the shape of the pulse spread out in space is identical to the shape of the signal in time at the generator terminals.

Transition to High Frequency

- When circuit components have size comparable to the wavelength (≥ $\lambda/5$), wave propagation effects and time delay effects will be felt and lumped picture of the components begins to fail.
- Simultaneously, transmission lines also need to be represented by distributed circuit elements.
- Such a system is governed by wave equations that support voltage and current waves on the line.

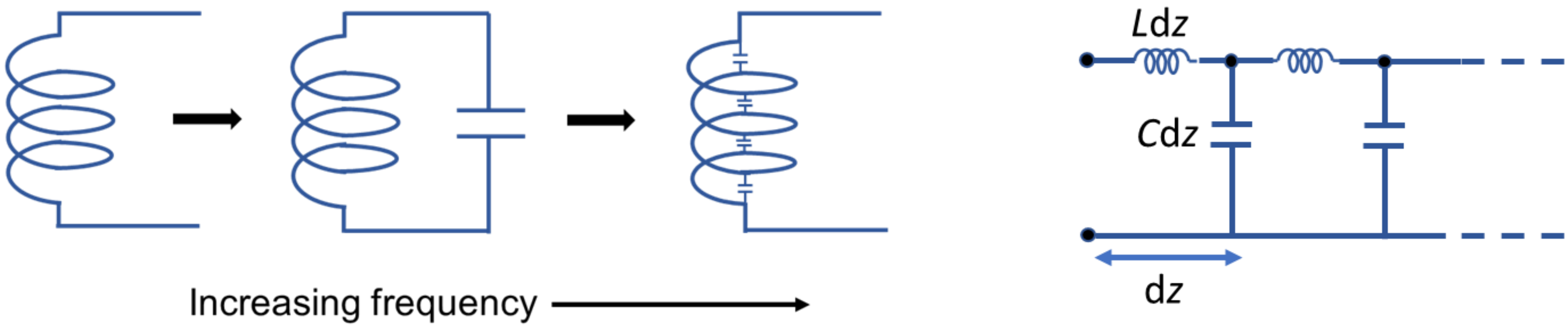
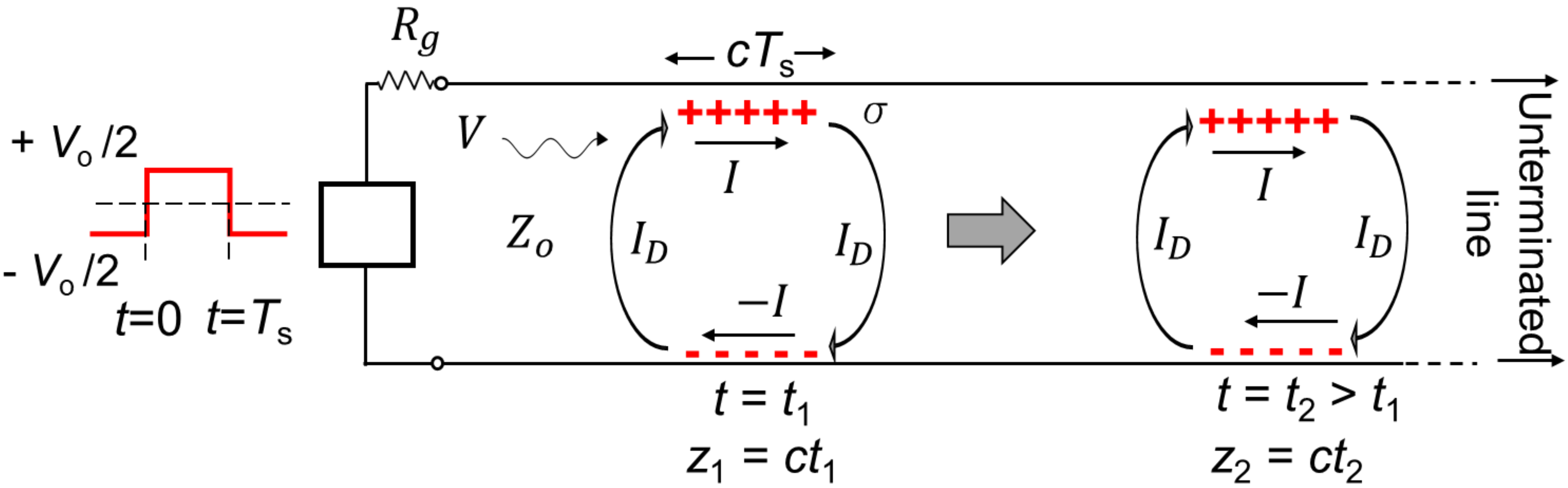


Figure shows how distributed circuit elements become important as frequency is increased.

Pulse propagation on ideal transmission line



Pulse propagation governed by wave equation

Voltage pulse height $V = V_o\, Z_o / (R_g + Z_o)$

Current pulse height $I = V / Z_o$

Line parameters

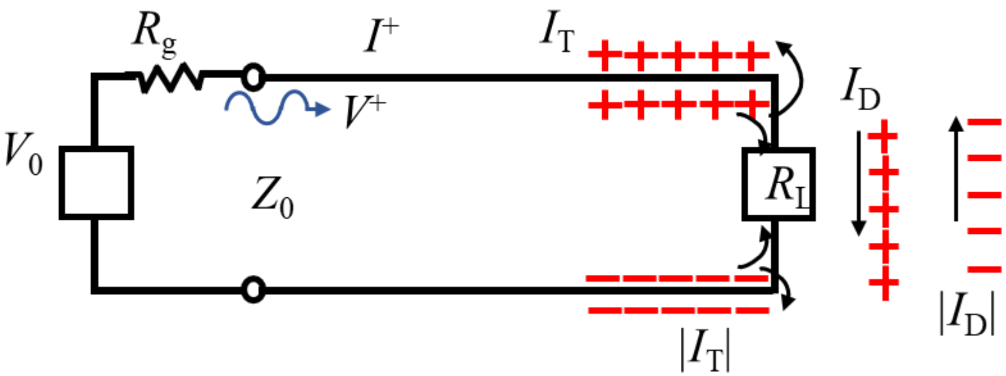
L : inductance/length

C : Capacitance/length

σ (Coul/m) = C^*V

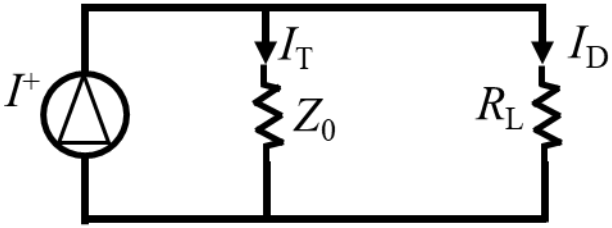
$$Z_o = \sqrt{\frac{L}{C}},\ c = \frac{1}{\sqrt{LC}}$$

$$I_D = \frac{\delta(\epsilon_o EA)}{\delta t} = \frac{\delta(\epsilon_o * Flux)}{\delta t} = \frac{\delta Q}{\delta t} = \frac{I\delta t}{\delta t} = I$$



$$V = V^+ + V^- \qquad I = I^+ - I^-$$

$$I^+ = \frac{V^+}{Z_0}, \quad I^- = \frac{V^-}{Z_0}$$



$$I_T = \frac{R_L}{Z_0 + R_L} I^+ \qquad I_D = \frac{Z_0}{Z_0 + R_L} I^+$$

Load current: $I_L = I_D + I_D = \dfrac{2Z_0}{R_L + Z_0} I^+$

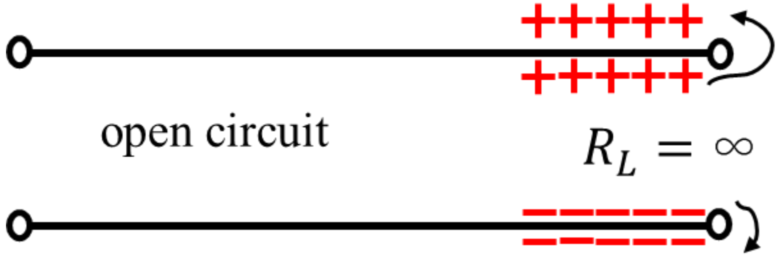
- I_D → -ve charge going up
- I_D → +ve charge coming down

Reflected current: $I^- = I_T - I_D = \dfrac{R_L - Z_0}{R_L + Z_0} I^+ = \rho_L I^+$ where $\rho_L = \dfrac{R_L - Z_0}{R_L + Z_0}$

- +ve charge turning back ← I_T
- -ve charge coming from bottom ← I_D

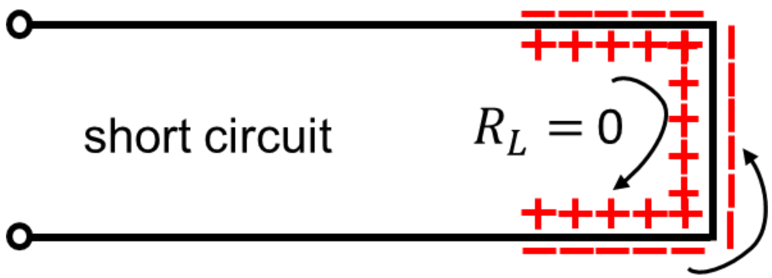
ρ_L = Current, Voltage reflection coefficient of load

Special Cases:



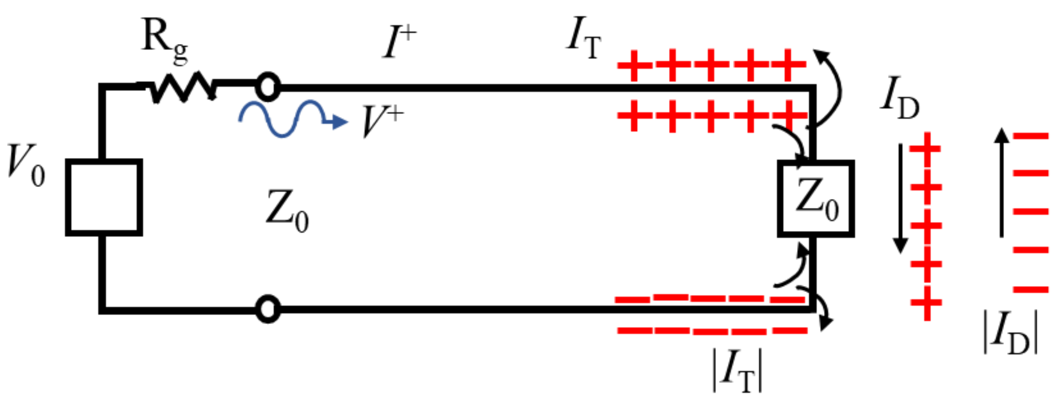
$I = 0\,,\ I^{+} = I^{-},\ V^{+} = V^{-}$

$V = V^{+} + V^{+} = 2V^{+}$



$V = 0, V^{+} = -V^{-}, I^{+} = -I^{-}$

$I = I^{+} - I^{-} = 2I^{+}$



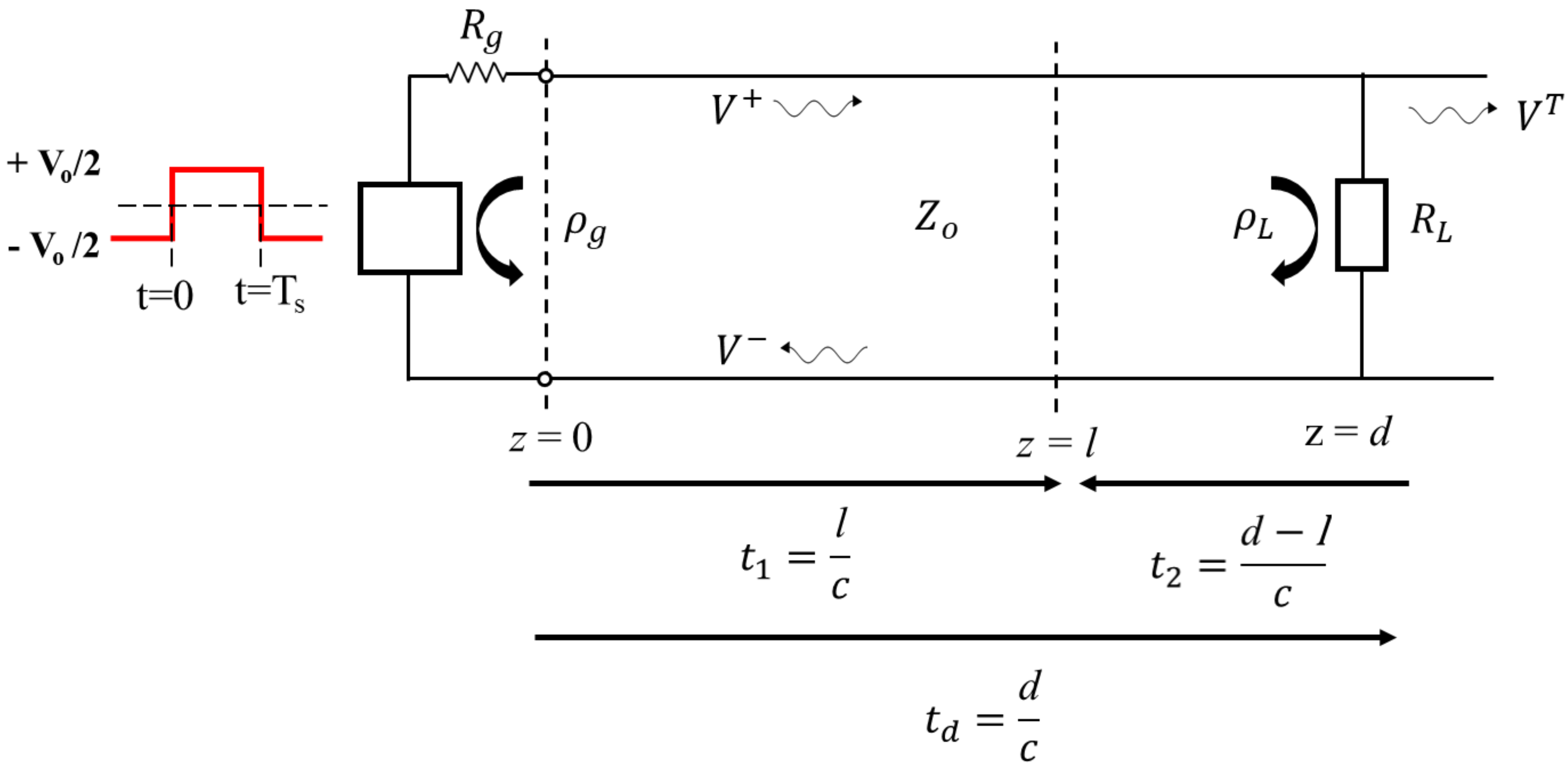
$I_T = I_D = I^{+}/2$

$I^{-} = I_T - I_D = 0$

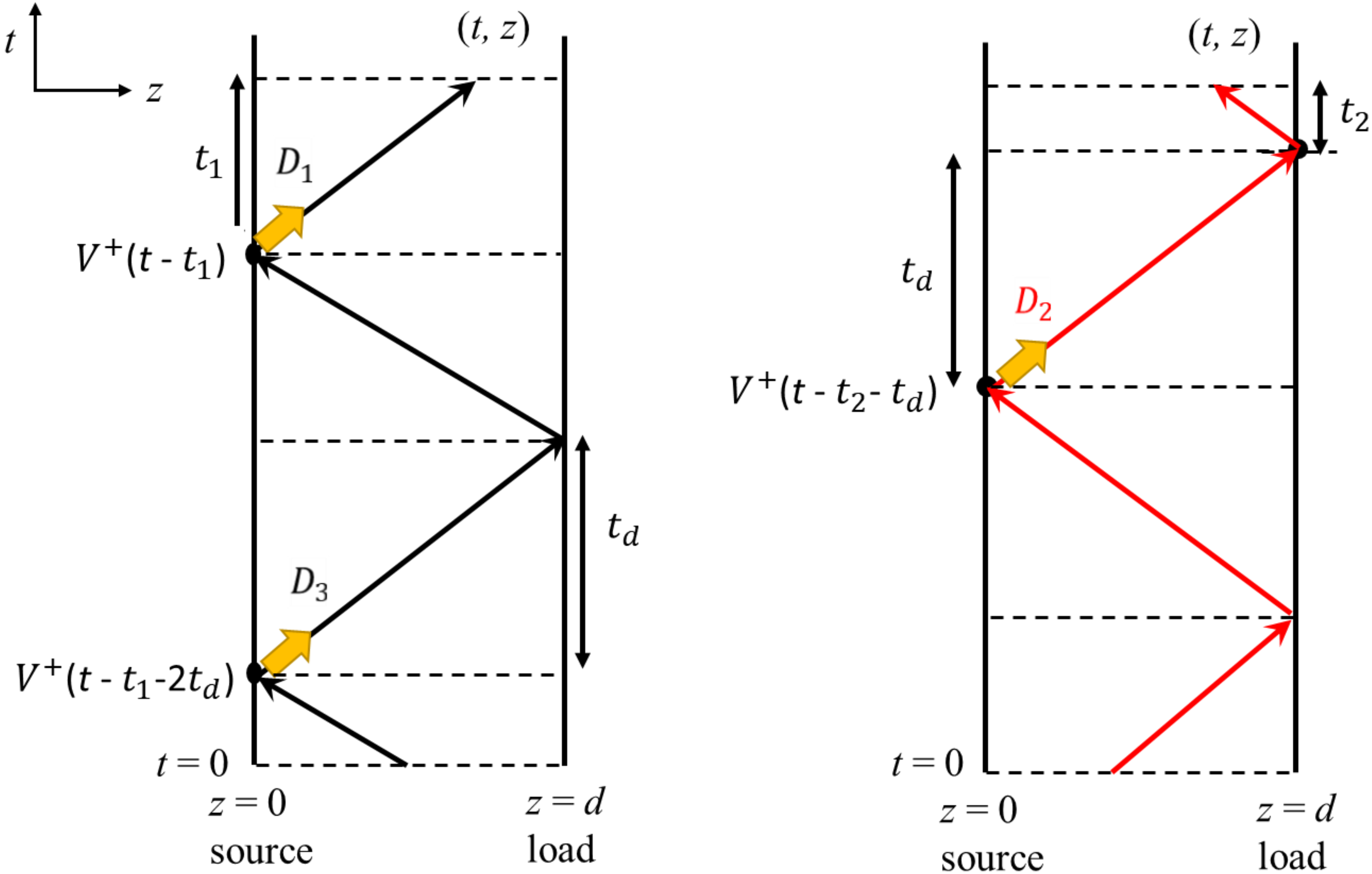
$V^{-} = 0$

So, no reflected pulse

Representation of transmission line



Arrival of signals at z at time t



D_1 = Voltage wave reaching z at time t directly from source

D_2 = Reaching z at time t after one reflection at load

D_3 = Reaching z at time t after reflections at load and generator

In the figure we saw that signals reach the field point (t, z) either from the source end or from the load end.
So total voltage V(t, z) is :

$$V(t,z) = V_1\ (t,z) + V_2(t,z)$$

$$V_1\ (t,z) = \ V^+(t - t_1) + V^+(t - t_1 - 2t_d) + V^+(t - t_1 - 4t_d) + \ldots\ldots$$

$$V_2\ (t,z) = V^+(t - t_2 - t_d)\rho_L + V^+(t - t_2 - 3t_d)\ \rho_L^2\ \rho_g + V^+(t - t_2 - 5t_d)\ \rho_L^3\ \rho_g^2 + \ldots\ldots$$

$V_1\ (t,z)$ is the sum of voltages reaching (t, z) from the source end.

$V_2\ (t,z)$ is the sum of voltages reaching (t, z) from the load end.

Low frequency approximation

At low frequencies, $t_s >> t_d$ The propagation delays are insignificant, so that $V^+(t - n\,t_d) \sim V^+(t)$ n = 1, 2, 3…….

With this approximation,

$$V(z,t) = \underbrace{V^+\left(1 + \rho_L\rho_g + \rho_L^2\,\rho_g^2 + \ \dots\right)}_{\text{Terms from source end}} + \underbrace{V^+\rho_L\left(1 + \rho_L\rho_g + \rho_L^2\,\rho_g^2 + \ \dots\right)}_{\text{Terms from load end}}$$

$$V(z,t) = \frac{V^+}{(1-\rho_L\rho_g)} + \frac{V^+\rho_L}{(1-\rho_L\rho_g)} = \frac{V^+\,(1+\rho_L)}{(1-\rho_L\rho_g)}$$

$$\boxed{\text{Using} \quad \rho_L = \frac{R_L - Z_o}{R_L + Z_o} \qquad \rho_g = \frac{R_g - Z_o}{R_g + Z_o} \qquad V^+ = V_o\,\frac{Z_o}{R_g + Z_L}}$$

$$V(z,t) = \frac{R_L}{R_L+Z_g}V_o$$

Which reproduces the voltage divider formula for low frequencies. Thus, RF analysis begins for $t_s \sim t_d$ so that propagation delay effects can no longer be ignored.

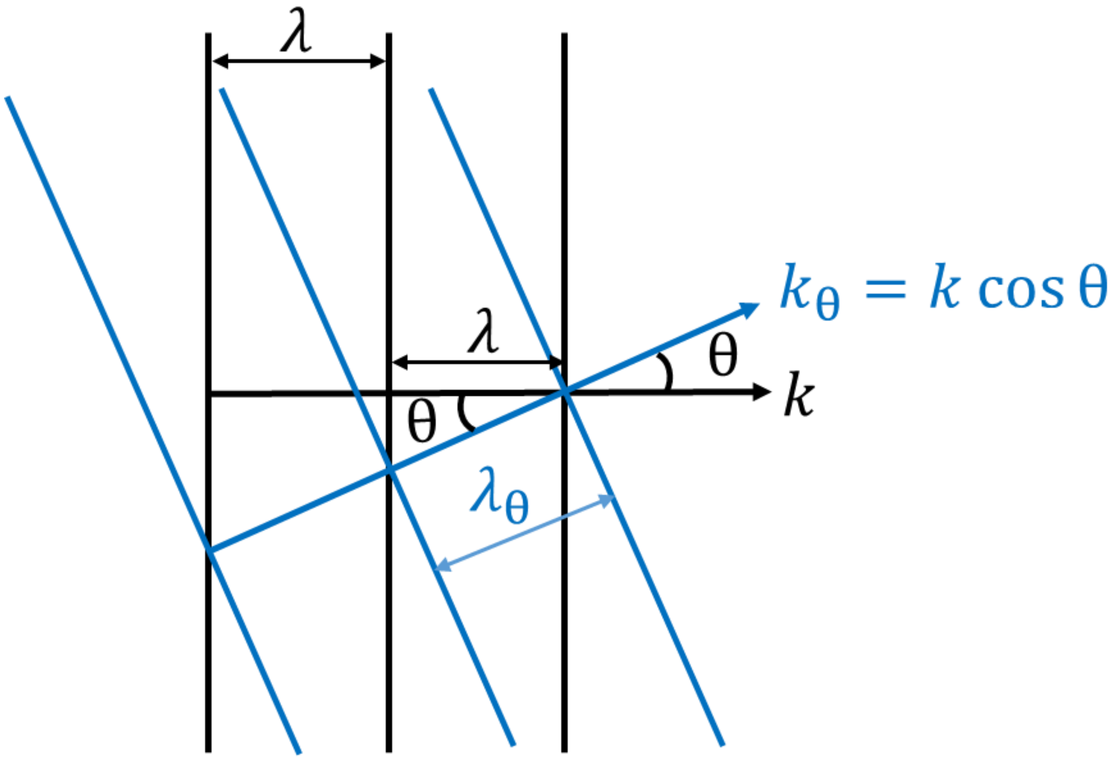
Wavelength of a plane wave at oblique angles from the direction of propagation

$\lambda = \lambda_\theta \cos\theta$

$\lambda_\theta = \dfrac{\lambda}{\cos\theta}$

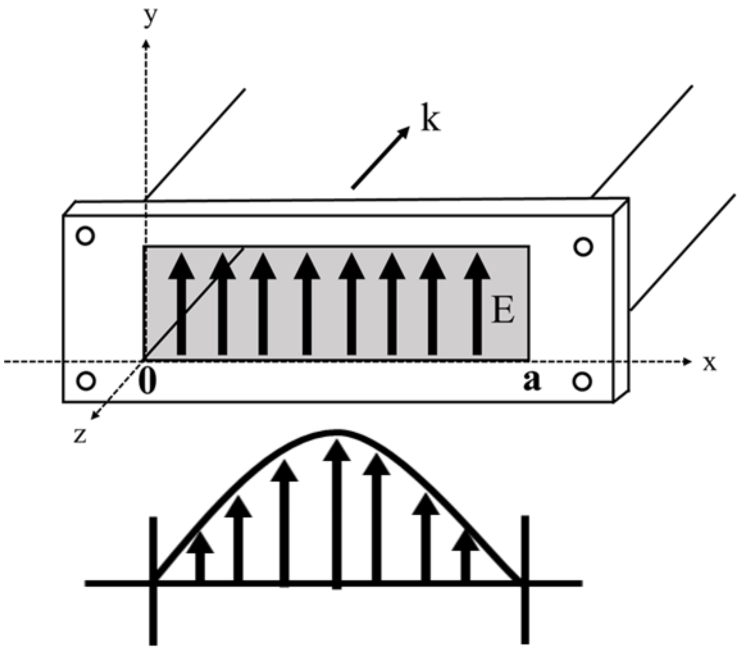
$k_\theta = \dfrac{2\pi}{\lambda_\theta} = \dfrac{2\pi}{\lambda}\cos\theta = k\cos\theta$

$\theta = 90^\circ \Rightarrow \lambda_\theta \to \infty$



Which implies that at $\theta = 90^\circ$ the value of the field is a constant.

Pushing a Plane Wave through a Rectangular Waveguide



For E polarized as shown in figure, boundary conditions on E demand that E vanish at the two tangential surfaces at x=0 and x=a.

For a plane wave directed along the waveguide axis, E would not be zero along the x-direction and so will not penetrate the guide.

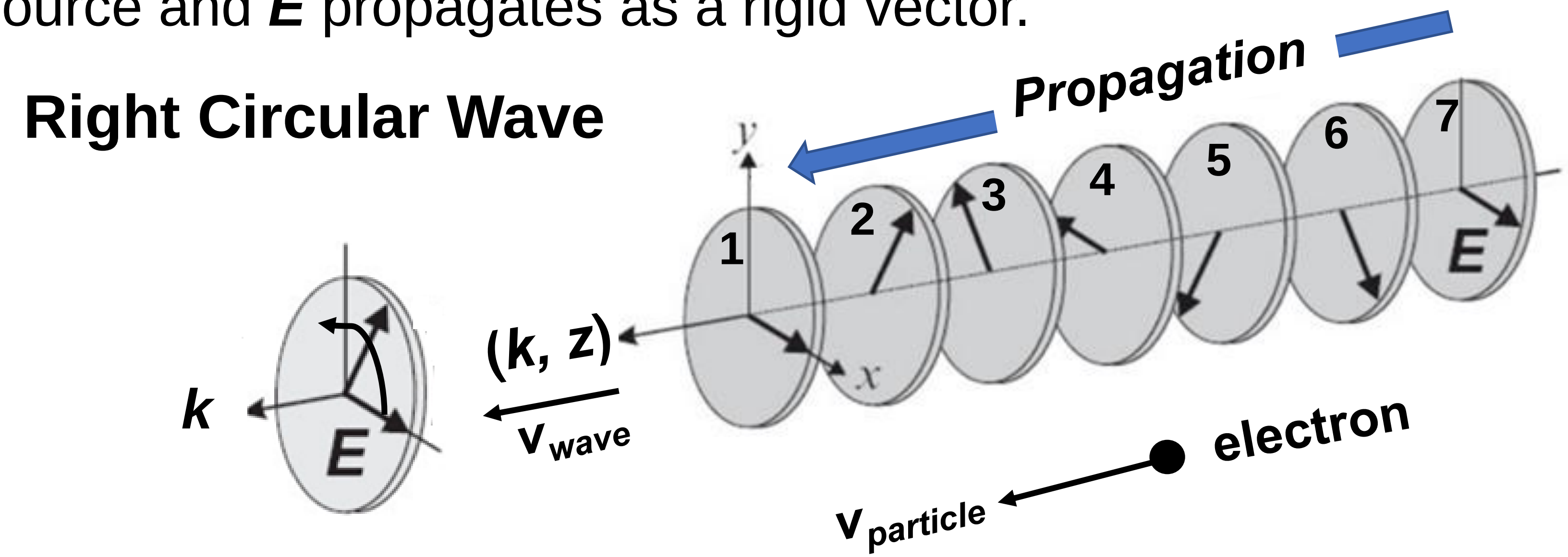
However if the wave enters the waveguide at an angle θ wrt x-axis, a spatial periodicity is induced along the x-direction, with $\lambda_x = \lambda_\theta = \frac{\lambda}{\cos\theta}$ which yields $\cos\theta = \frac{\lambda}{\lambda_x}$

To satisfy the boundary conditions on E, it is sufficient to choose $\lambda_x = 2a$. Then, the guide wavelength $\lambda_z = \frac{\lambda}{\sin\theta} = \frac{\lambda}{\sqrt{1 - cos^2\theta}} = \frac{\lambda}{\sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}}$

Which is the guide wavelength for the TE_{10} mode.

Propagation of Circularly Polarized Waves

At a fixed position ***E*** rotates in time. But during propagation, the orientation of ***E*** is locked to that at the instant of launching at the source and ***E*** propagates as a rigid vector.



$v_{particle} < v_{wave}$ → Particle observes *E* in the sequence 1-2-3-4-5-6-7 (RCP)
$v_{particle} > v_{wave}$ → Particle observes *E* in the sequence 7-6-5-4-3-2-1 (LCP)

So, for ECRH where electrons execute right handed rotation, only the slow electrons would absorb energy from the wave while fast electrons would see a left polarized wave and hence be unable to absorb energy from the wave.

Application to ECRH

- In a plasma filled circular guide, polarization reversal can occur along the radius.

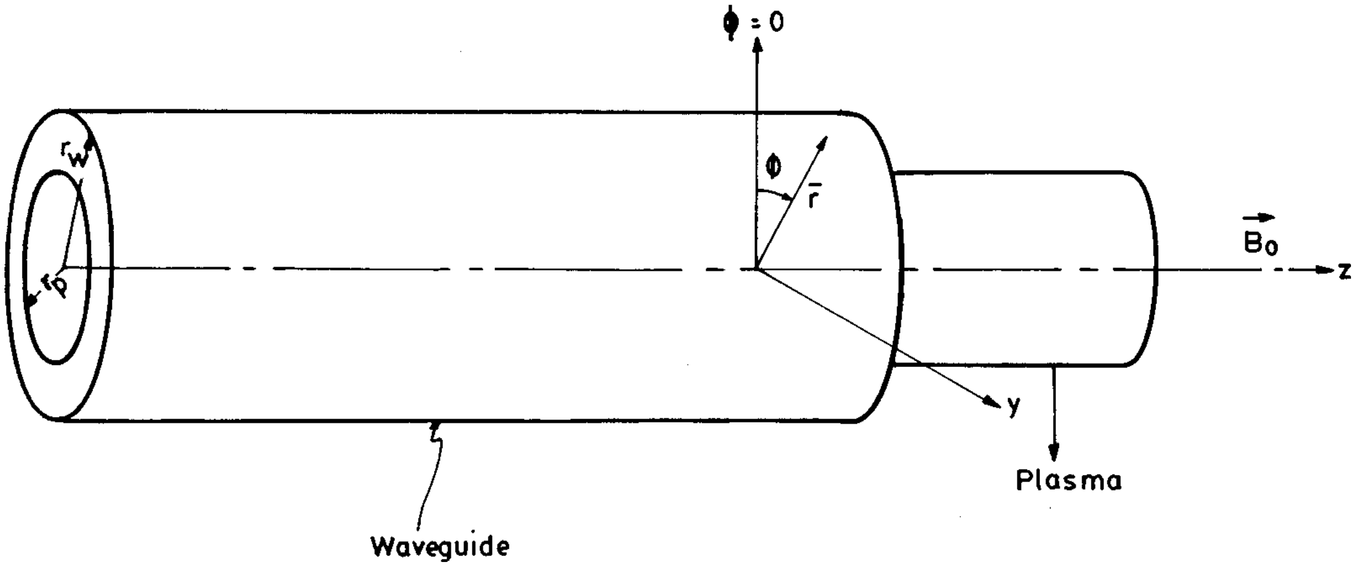
- For instance, a wave RCP on the axis can become linearly polarized or even LCP, with increasing radius inside the plasma.

- Similarly, reverse situation can also occur, where a wave LCP on axis can become RCP away from the axis.

- In regions where the wave is RCP, particles slower than the wave will absorb RF energy. But in regions where polarization is LCP, particles faster than the wave will absorb energy.

- Since electrons have a Maxwellian distribution, both slow and fast electrons will be present and so absorption can proceed with both types of polarization in the plasma.

Plasma model for ECR calculations



Polarization index

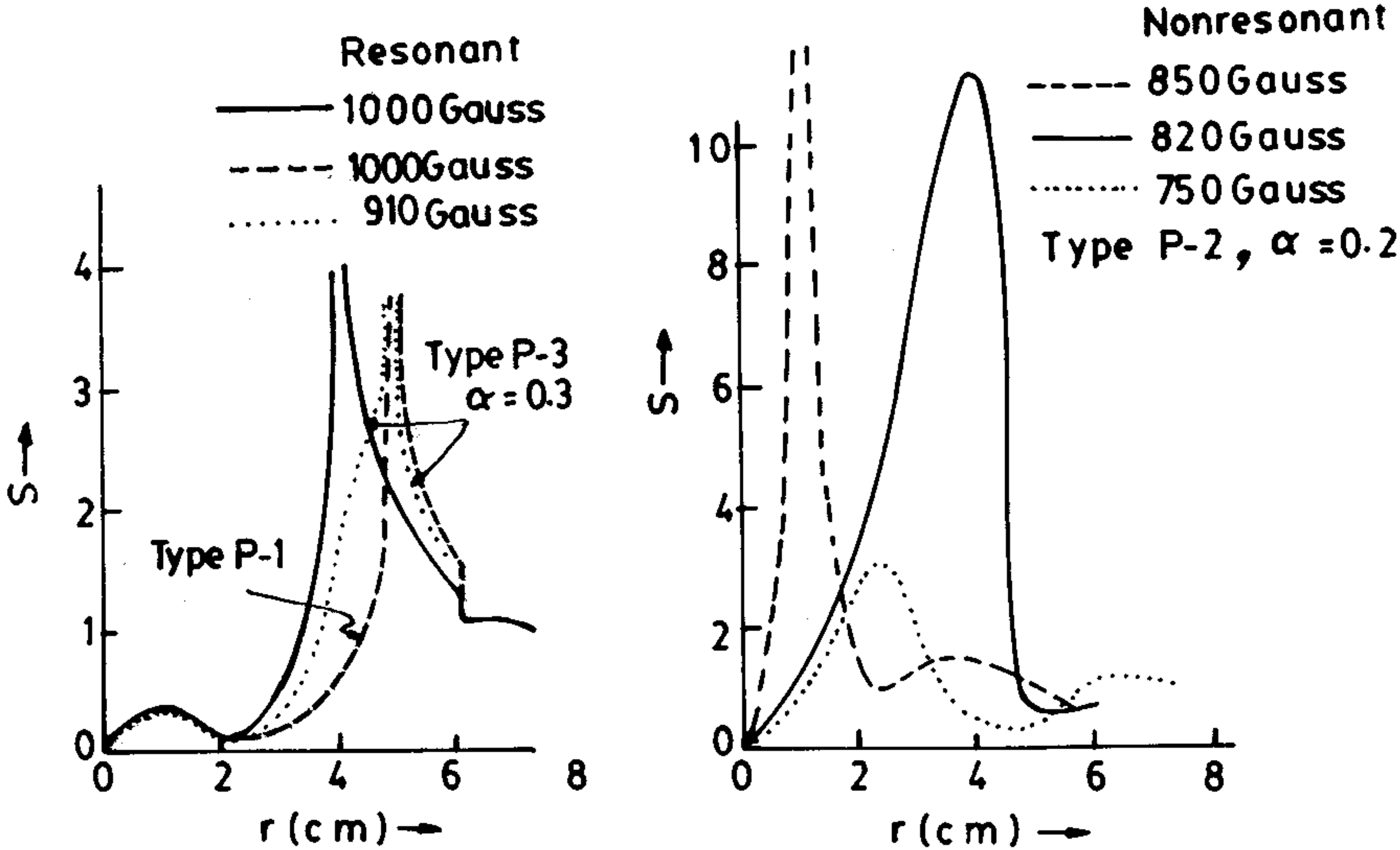
$$S = \frac{|E_r + iE_\emptyset|}{|E_r - iE_\emptyset|}$$

$0 < S < 1$ Right hand (elliptic) polarization
$S = 0$ Right circular polarization
$S = 1$ Linear polarization
$1 < S < \infty$ Left hand (elliptic) polarization
$S = \infty$ Left circular polarization

Ganguli et al. Physics of Plasmas 5, 1178 (1998)

Calculated radial profiles of Polarization

m = +1, r_p = 6 cm



Radial profiles of the polarization index S for the mode =+1.

Ganguli et al. Physics of Plasmas 5, 1178 (1998)

Experimental results of plasma production using RCP (m = +1) and LCP (m = -1) polarized waves in cylindrical wave guides

Table 1
Plasma characterization results (argon gas pressure: $\approx 5 \times 10^{-5}$ Torr; plasma radius: ≈ 7 cm)

Mode (discharge)	Power (W)	Plasma density $\times 10^{11}$ (cm^{-3})	Bulk electron temperature (eV)	Warm electron density $\times 10^{9}$ (cm^{-3})	Warm electron temperature (eV)	Radial profile coefficient (α)
$m = +1$(RD)	263	(1.2–2.0)	(8–4)	(1.0–4.0)	(20–30)	≈ 0.4
$m = +1$(NRD)	315	(5.0–9.0)	(15–20)	Single	component	≈ 0.4
$m = -1$(RD)	230	(2.5–4.0)	(3–5)	(0.8–2.0)	(25–35)	≈ 0.4
$m = -1$(NRD)	277	(0.7–1.0)	(5–10)	(2.0–7.0)	(30–50)	≈ 0.3
Theoretical values		1.0	5	1.0	40	≈ 0.1–0.4

- The experimental results show that the plasma densities obtained using either on-axis polarization (LCP/RCP) are very similar indicating that energy absorption from the wave is efficient for both.
- Since polarization reversal occurs for both cases, in the regions with right hand polarization wave absorption occurs due to slow electrons, whereas in regions with left hand polarization wave energy absorption can proceed through electrons travelling faster than the wave.

Ganguli et al. *Phys. Lett.* A 250 (1998)

Application to excitation of RCP helicon waves using phased loop antennas

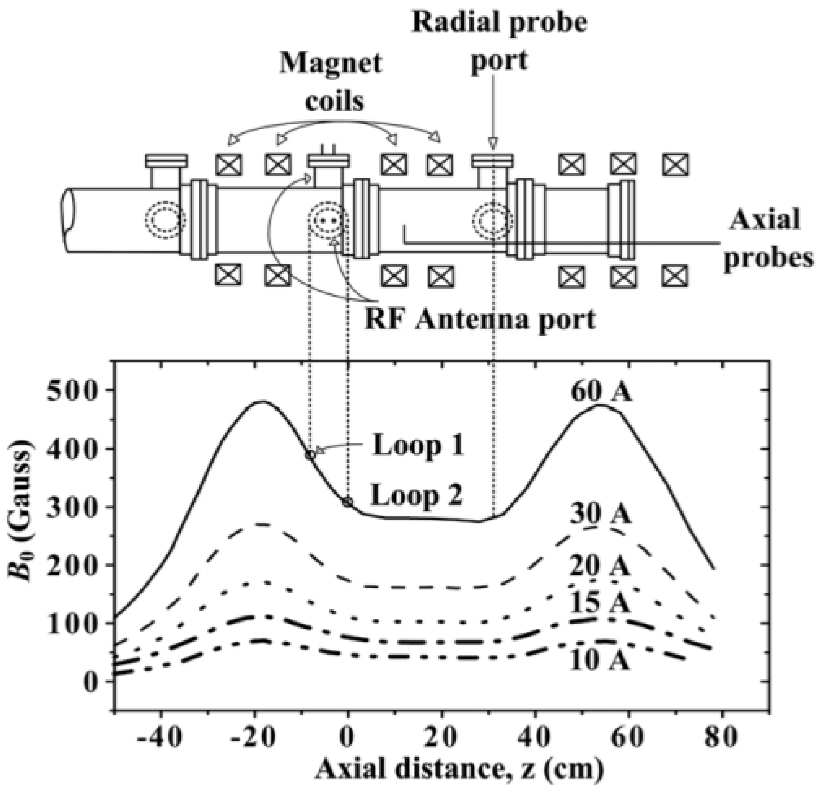


Figure 1. Schematic diagram of the experimental system showing location of the loop antennas and chamber ports in relation to the axial magnetic field (B_0) profiles at various coil currents.

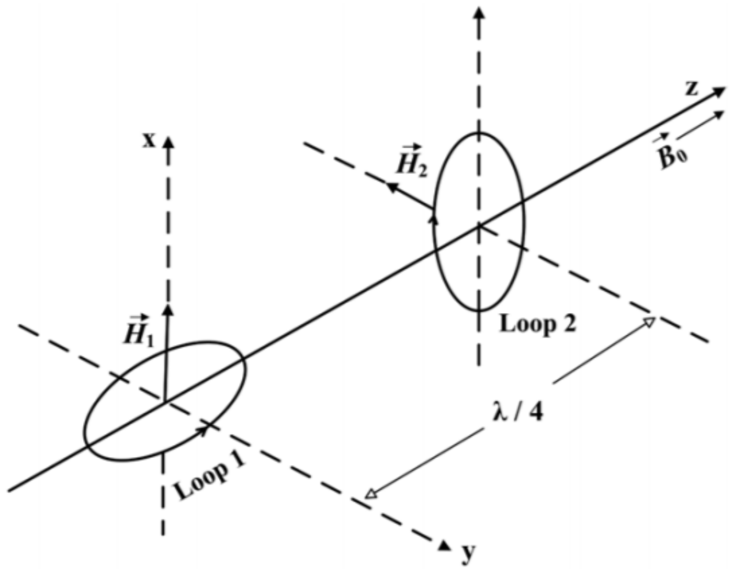
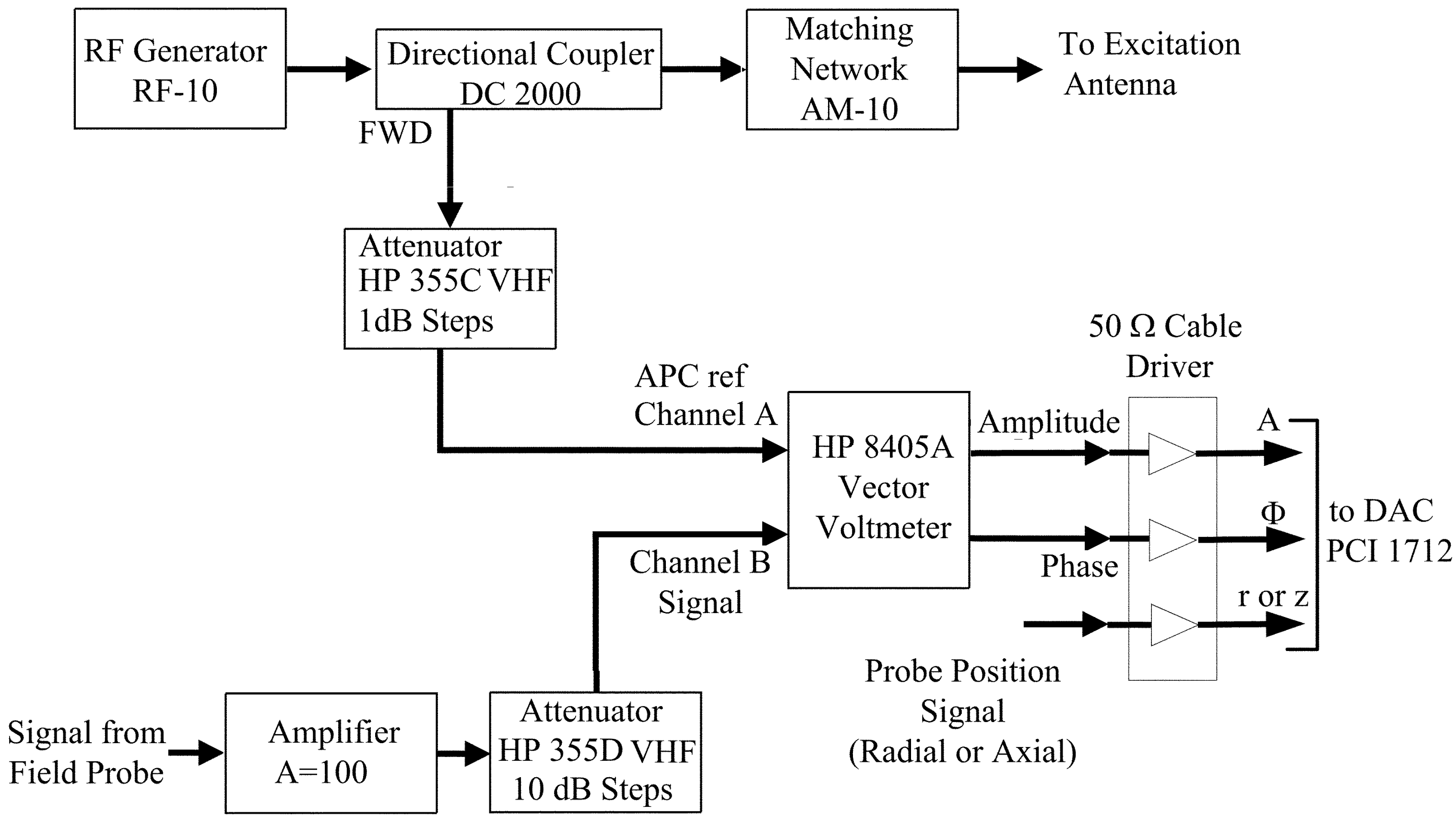


Figure 2. Orientation of the two loop antennas for excitation of the $m = -1$ azimuthal mode (RCP); loop 1 is in the y–z plane and loop 2 is in the x–y plane; the separation is such that the IPS is $\pi/2$.

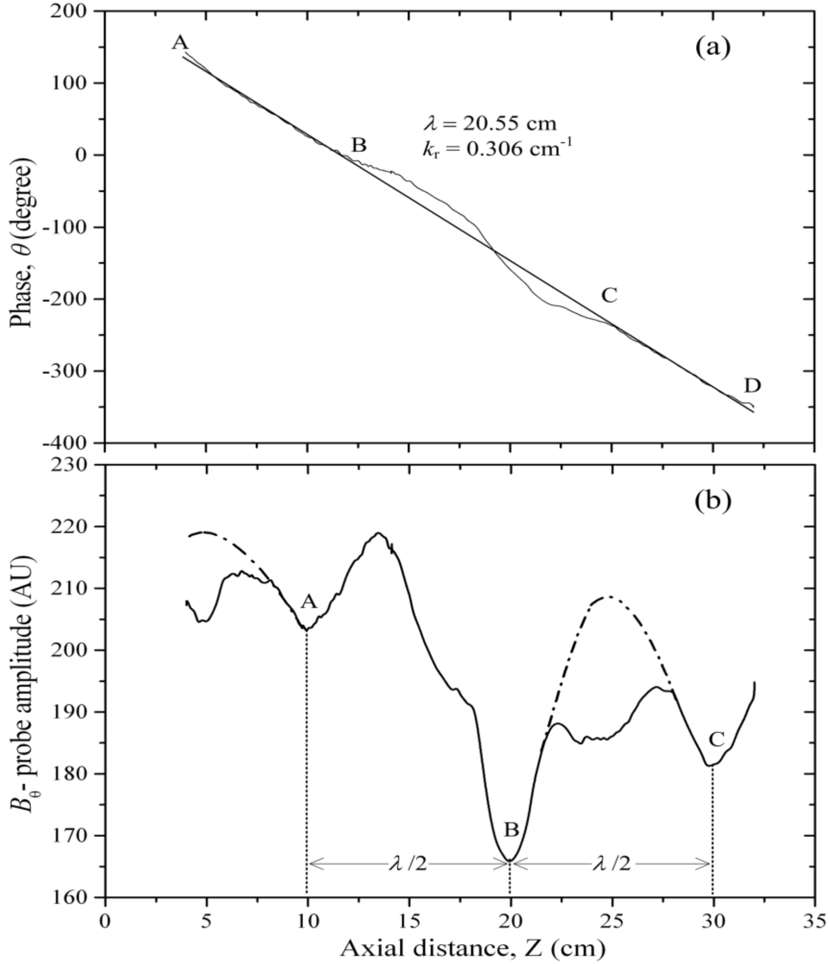
Ganguli et al. *Plasma Sources Sci. Technol*. 015021 **20** (2011)

Wavelength measurements



A block diagram of the wavelength measurement scheme using the vector voltmeter at 13.56 MHz.

Wavelength measured at low pressures



The phase plot shows presence of a traveling wave with wavelength about 20 cm.

However, the amplitude plot shows presence of standing wave as well.

Frequency = 13.56 MHz

Axial variation of the (a) phase and (b) amplitude using the B-dot probe at $B_0 \approx 20$ G, 0.3 mTorr pressure and 940 W RF power.

Thank You