Finite element modeling of remote field eddy current phenomenon

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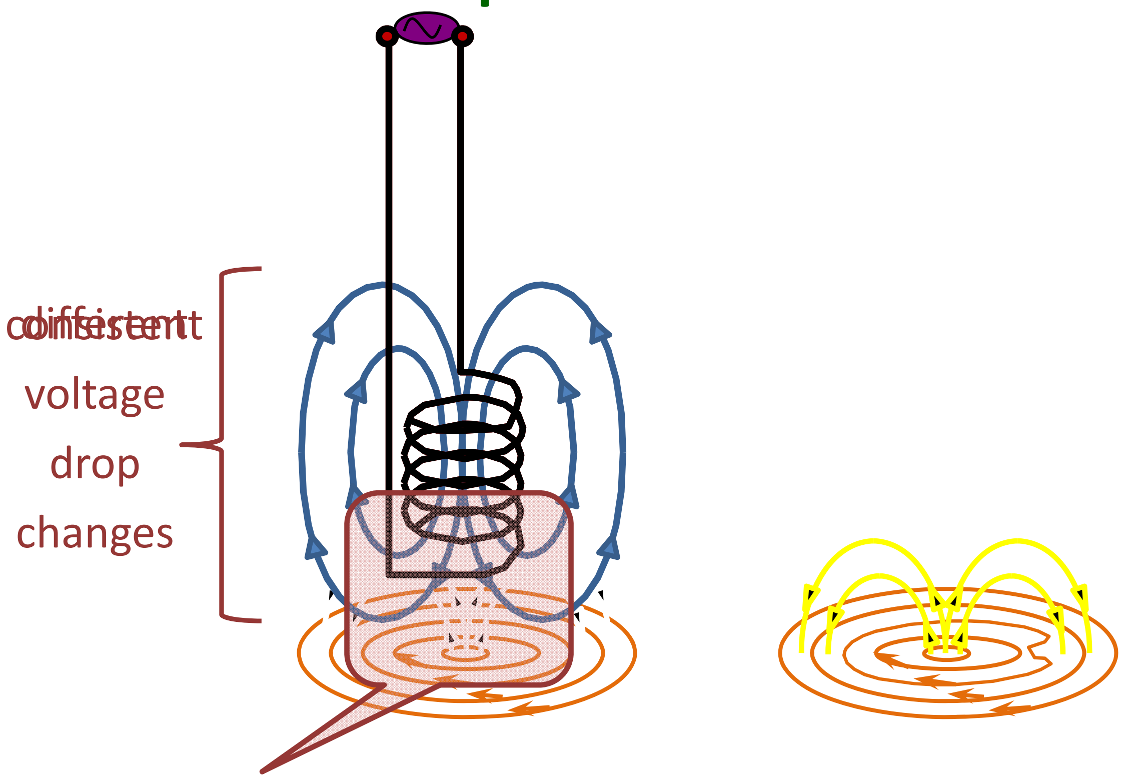
Outline of presentation

- Introduction to eddy current testing
- Introduction to remote field eddy current testing
- Governing PDE of Remote field eddy current testing
- Modeling RFEC technique in COMSOL
- Analysis of model predictions
- Conclusions and further works

Eddy current testing principles

Used for nondestructive detection of defects and anomalies in metallic materials and components



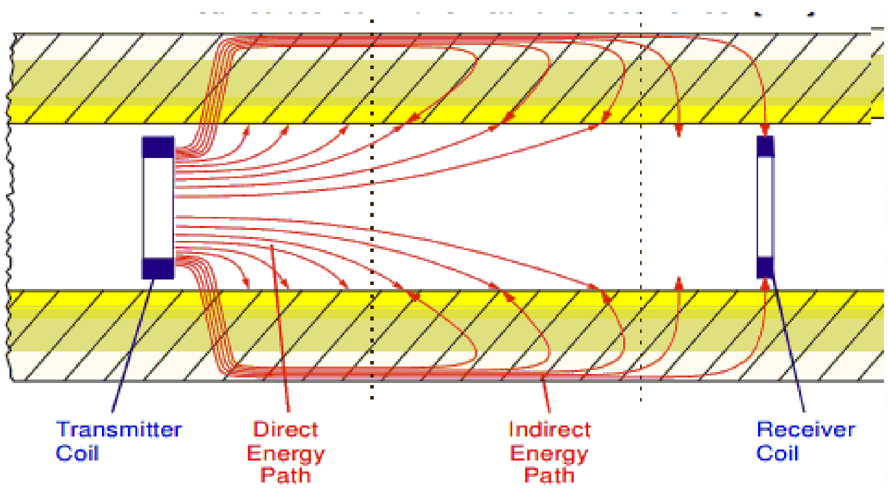
- **Probe/coil**
- **Sinusoidal excitation source**
- **Sets up a Primary field**
- **Eddy currents induced in the material**

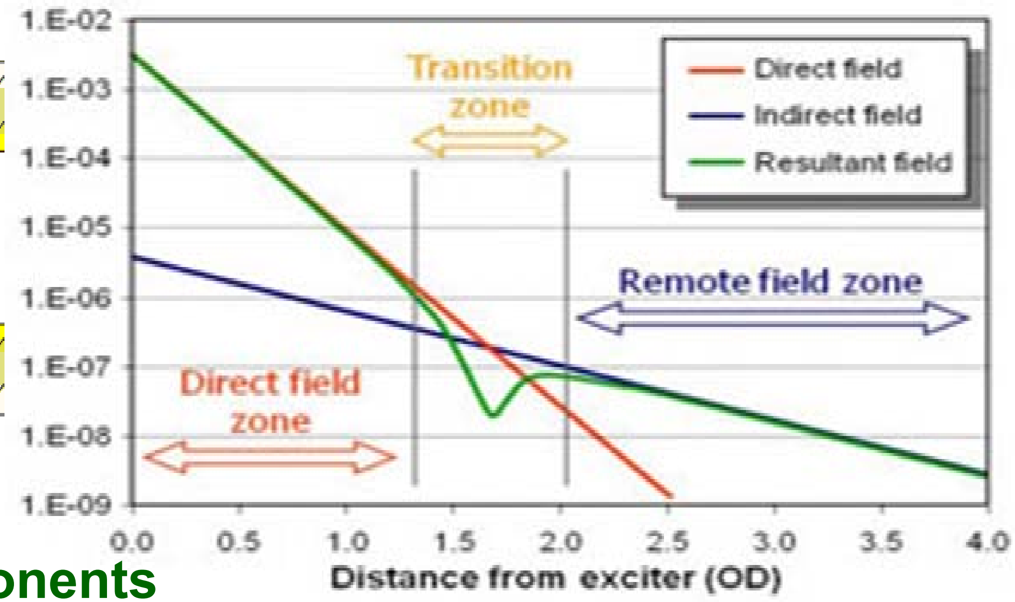
✓ ***Lenz's law:***

An induced electromotive force (emf) always gives rise to a current whose magnetic field opposes the original change in magnetic flux.

Impedance change of the coil is measured with respect to defect and defect –free regions to detect them.

Introduction to RFEC technique (A variant of eddy current testing with exciter-receiver coils)





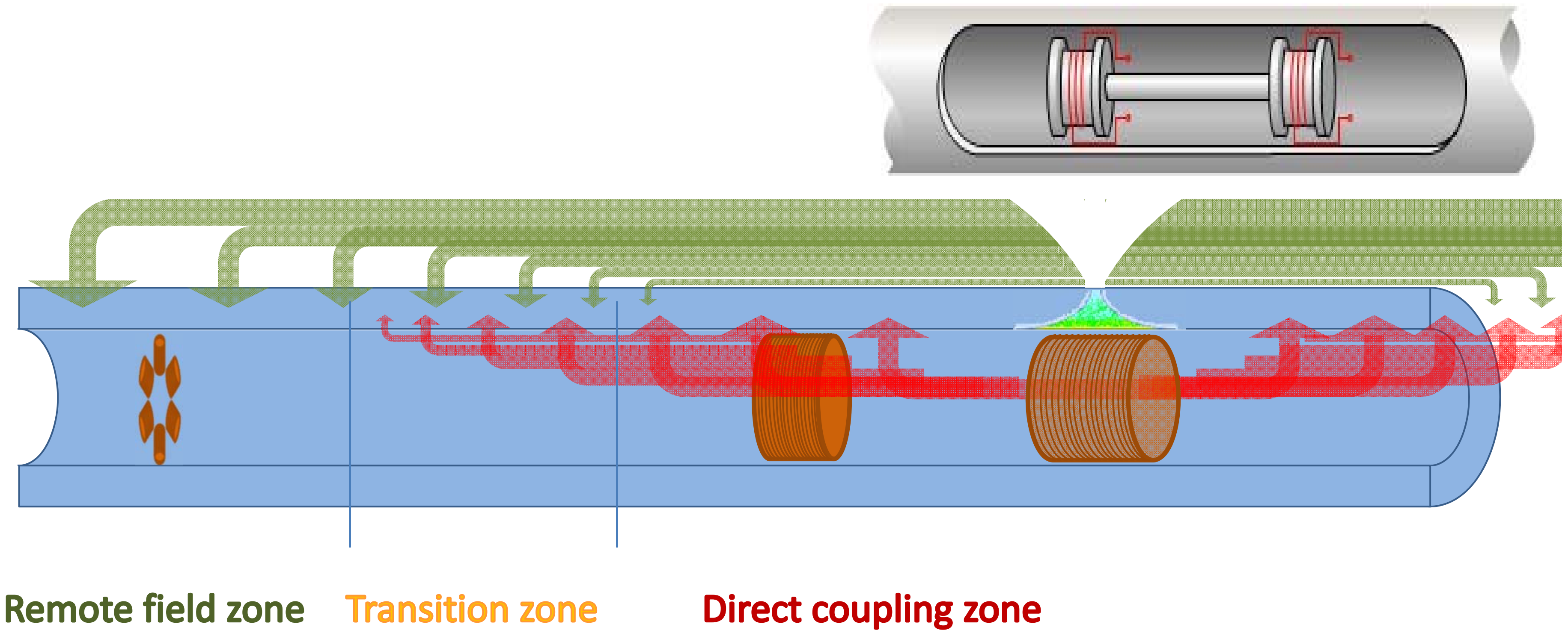
For tubular ferromagnetic components

Sinusoidal excitation of the coil establish two different fields of interest

1) **Direct field/energy is due to the excitation coil**
2) **Indirect field/energy due to eddy currents in the tube**

- ✓ **The indirect field is dominant at the remote field zone**
- ✓ **This phenomenon happen due to the different attenuation characteristics of air and the magnetic materials**

Remote field eddy current technique- Principle



- ➢ **The receiver coil is kept in the remote field zone avoiding direct coupling and transition zones for detecting defects in the tube wall.**
- ➢ **Identification of this remote field zone is primary objective of the COMSOL model**

FE Modeling of RFEC - Formalism

Maxwell's curl equations

$$\nabla \times \overline{E} = -\frac{\partial \overline{B}}{\partial t}$$

$$\nabla \times \overline{H} = \overline{J}$$

$$\overline{B} = \nabla \times \overline{A}$$

$$\overline{J} = \overline{J}_s + \overline{J}_e$$

$$\overline{E} = -\frac{\partial \overline{A}}{\partial t} - \nabla V$$

$$\overline{J}_e = \sigma \overline{E}$$

Where E is the electric field
B is magnetic field and
A is magnetic vector potential
J is the current density

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \overline{A} \right) = -\sigma \frac{\partial \overline{A}}{\partial t} - \nabla \sigma V + \overline{J}_s$$

Assuming μ to be constant and incorporating Coulomb gauge condition Δ.A=0

$$\nabla^2 \overline{A} = \mu\sigma \frac{\partial \overline{A}}{\partial t} + \mu\sigma \nabla V - \mu \overline{J} s$$

$$Time \quad harmonic \quad fields \quad \left(A = e^{-i\omega t} \right) \quad \frac{\partial \overline{A}}{\partial t} = i\omega \overline{A}$$

$$\nabla^2 \overline{A} = i\mu\sigma\omega \overline{A} + \mu\sigma \nabla V + \mu \overline{J} s$$

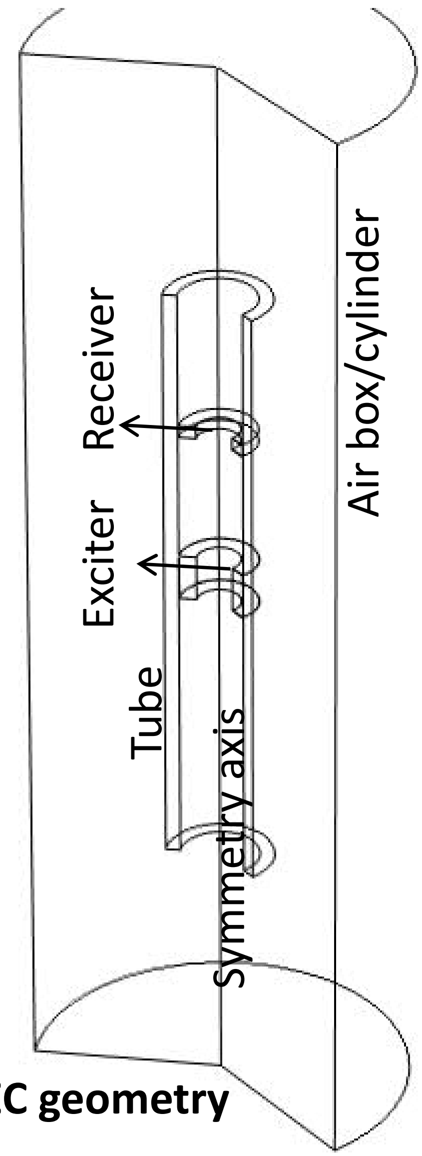
Source current density (J_s) is a constant value

FE Modeling – 2D axisymmetric

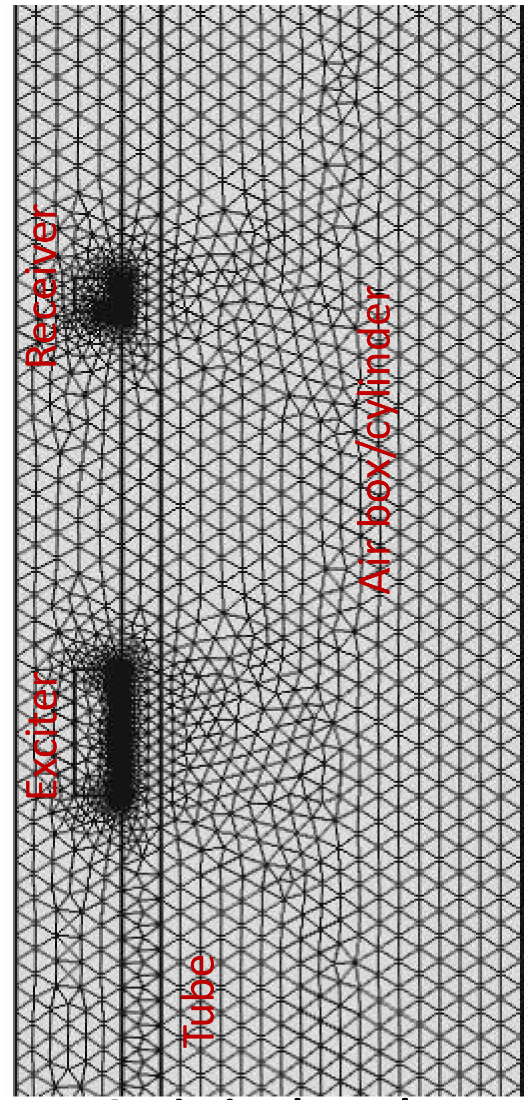
Material properties used in the model

Geometry	Size (Width x Height mm)	Property
Exciter coil	2.7 x 7.5	Copper
Tube	2.3 x 100 (ID. 12.6 mm)	Mod. 9Cr-1Mo
Outer box	30 x 110	Air

Number of turns in exciter coil : 400, SWG 38
Number of turns in receiver coil : 200, SWG 38
Current in exciter coil : 100 mA



RFEC geometry



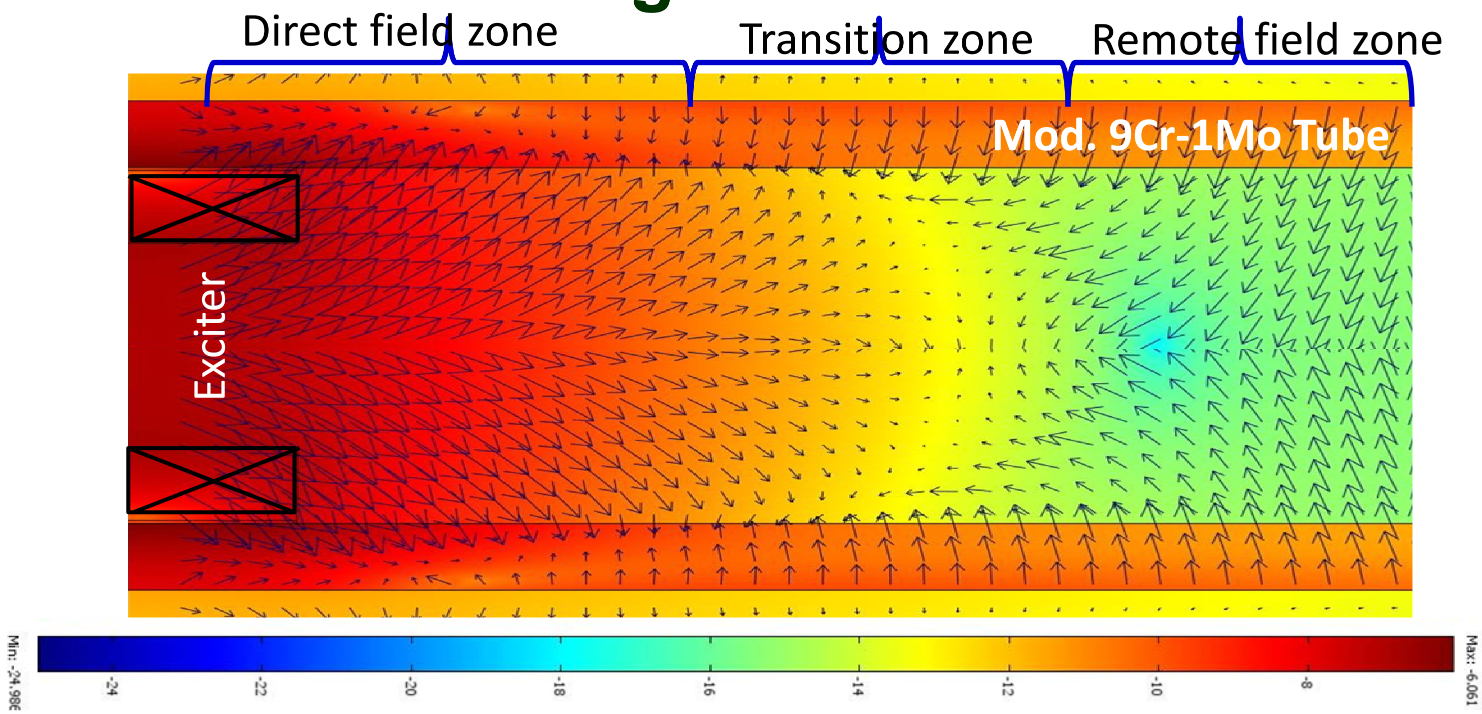
Optimized Mesh

Material property and boundary condition

Geometry	Property	Conductivity, S/m	Relative permeability
Coil	Copper	6.0×10^7	1
Tube	Mod. 9Cr-1Mo steel	2.3×10^7	75
Outer box	Air	100	1

- **The conductivity of the air chosen to be very small (not zero) to maintain numerical stability (zero on diagonal, ill conditioning of matrix)**
- **Electric insulation boundary condition (Neumann condition on magnetic filed) used against magnetic insulation which required larger solution domain)**
- **Solver: Direct (UMFPACK) solver for sparse matrix**
- **The Magnetic vector potential (A_ϕ) values obtained after solving the model at the nodal points used for further processing.**

Analysis of the predicted magnetic flux density, Magnetic field

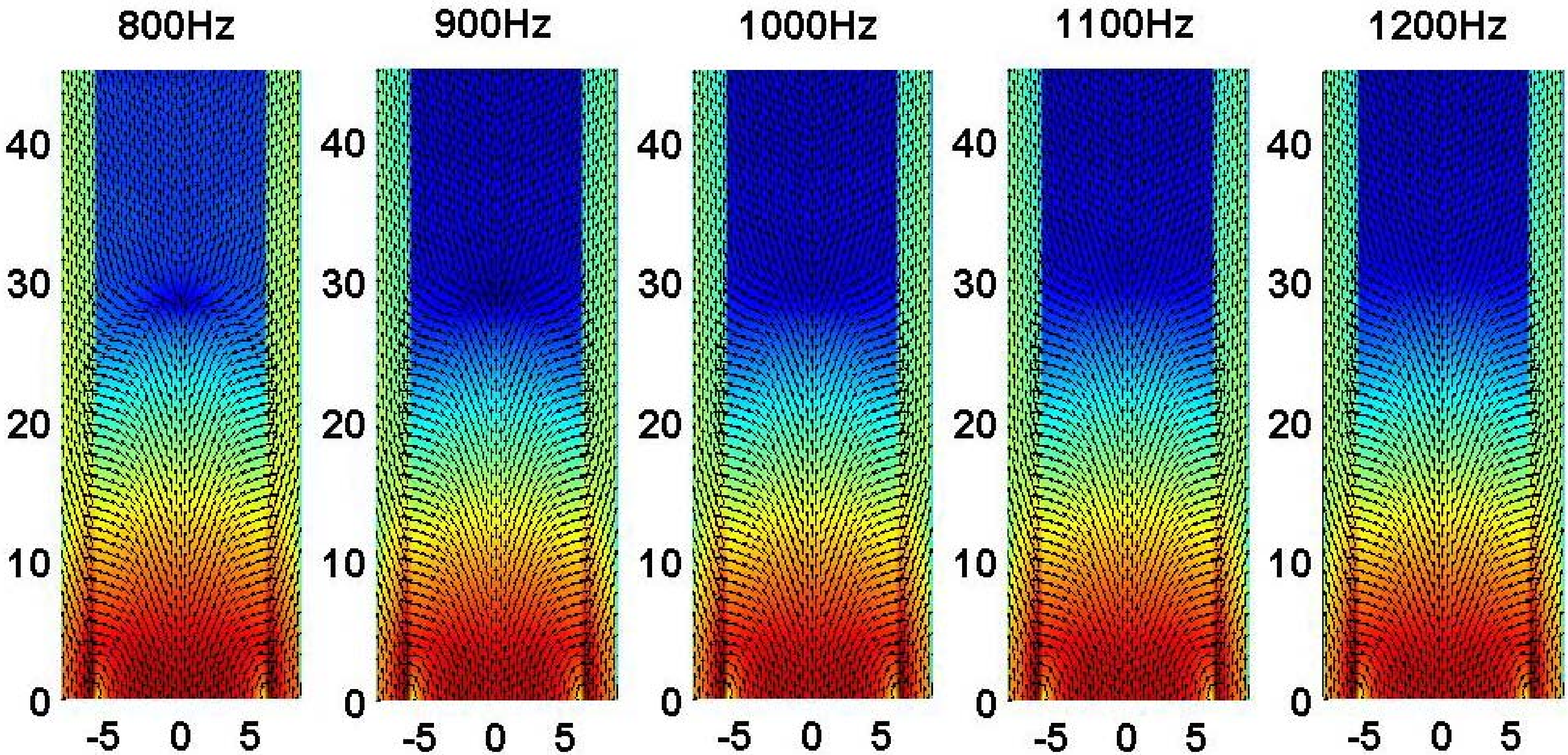


Surface plot : logarithm Magnetic flux density (Magnitude information)

Arrow plot : logartihm Magnetic field (direction information)

- **Close to the exciter coil the direct field is dominant and indirect or the resultant field is minimum.**
- **With increase axial distance the indirect fields increase and direct field decrease.**
- **At the remote field zone the indirect field is dominant and enters back into the tube ID.**

Analysis of the predicted magnetic flux density and field at different frequencies



- **Predicted field profiles confirms the existence of RFEC zone in the ferromagnetic tubes**

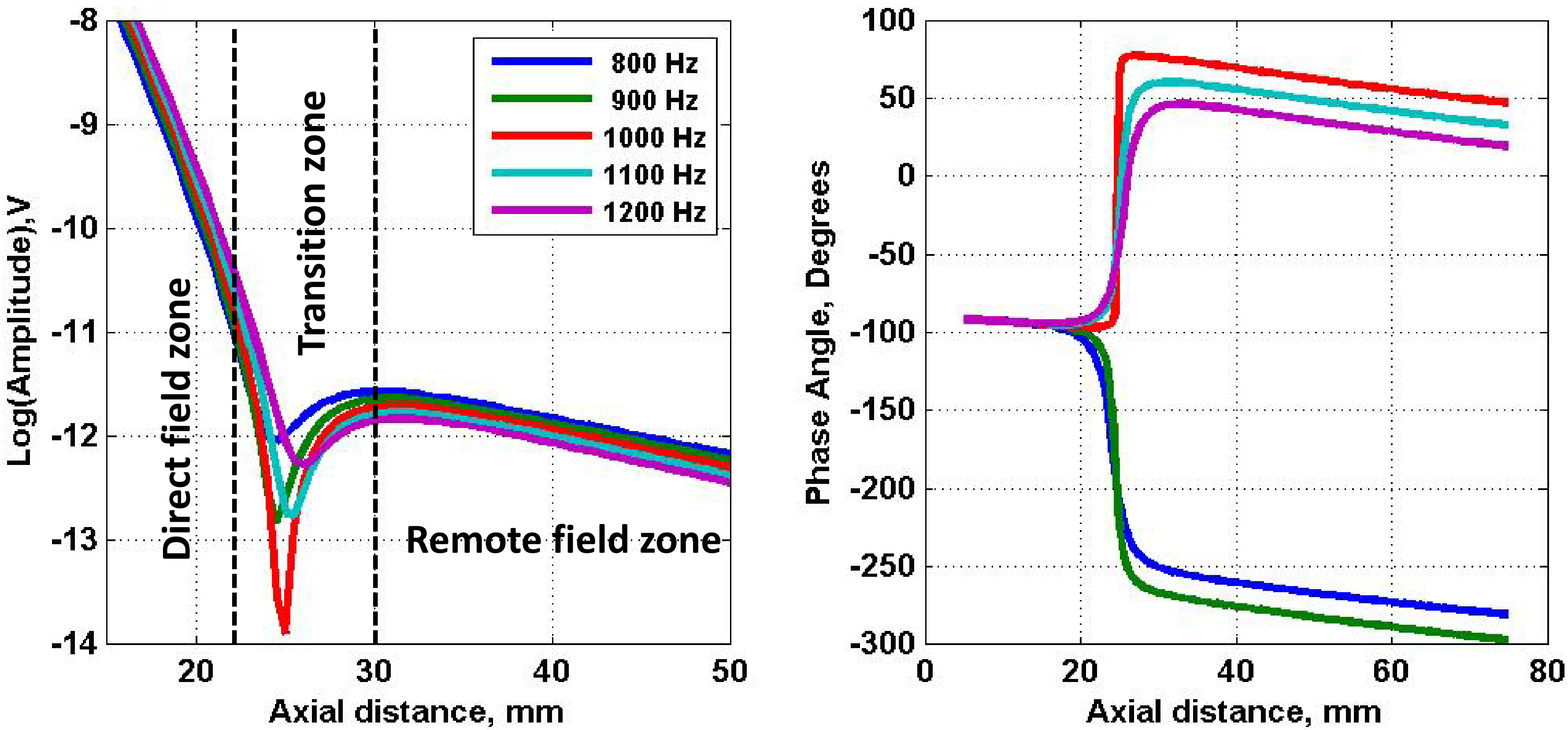
Analysis methodology for obtaining the RFEC characteristics

- **Further characteristics of the RFEC technique analyzed in the following manner:**

- **Vector potential values inside the tube were used to calculate amplitude and phase of the induced voltage in the fictitious receiver coil at different axial positions.**
- **log (amplitude) and phase angle plotted as a function of the axial position of the receiver coil.**

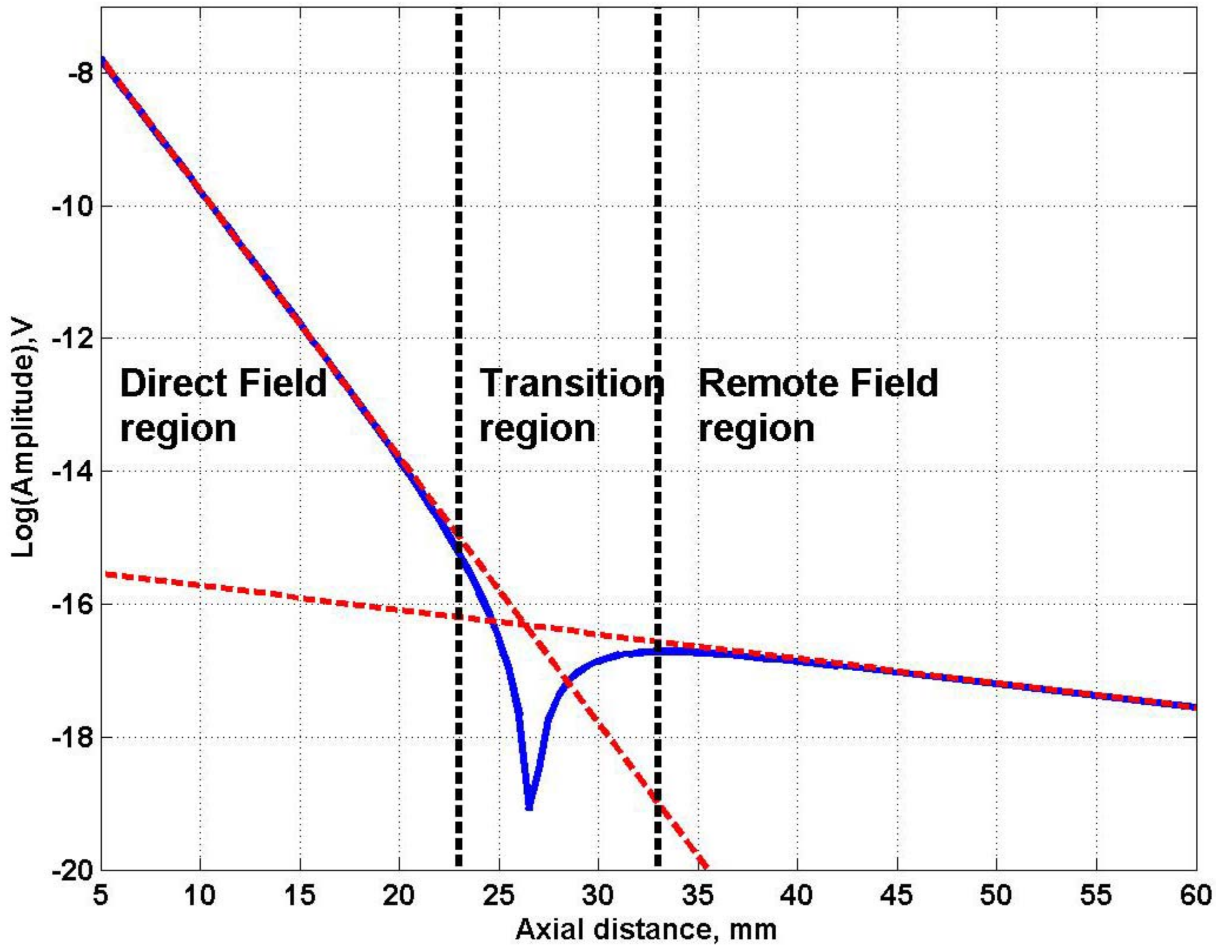
$$Induced\ \ voltage = -N\frac{d\phi}{dt} = -Ni\,\omega\oiint B.da = -Ni\,\omega\oiint \nabla\times A.da = -Ni\,\omega\oint A.dl = -Ni\,\omega A.2\pi r$$

Amplitude and phase of induced voltage in axially displaced receiver coil



- Clear distinction of direct, transition and RFEC zone observed.
- The phase angle shows a sudden jump of nearly 180 degrees
- Phase angle jump signifies the back entry of indirect field due to eddy currents in the tube wall

Quantitative characterization of RFEC zone



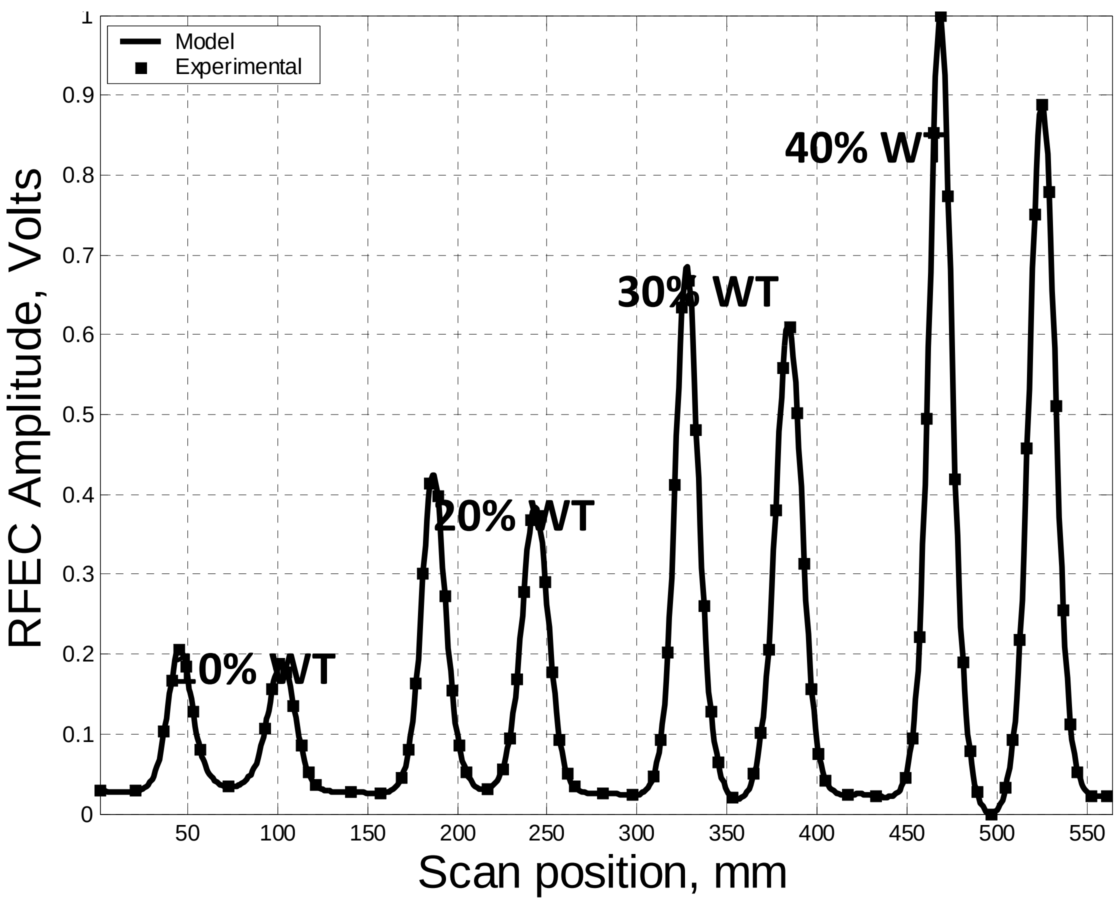
- **Deviations in the straight line behavior in the direct and remote field zones was quantitatively analyzed to characterize the zone**

Presentation of quantitative Analysis results

S. No.	Frequency, Hz	Start of transition region (A), mm	End of transition region (B), mm
1	500	21.5	40.0
2	600	20.0	38.0
3	700	19.5	36.5
4	800	19.0	36.0
5	900	19.0	35.5
6	1000	19.5	35.0
7	1100	19.5	35.0
8	1200	20.0	34.5
9	1300	20.0	34.0
10	1400	21.0	33.5
11	1500	22.0	32.0

- **The transition zone ends at 35 mm in most of the frequencies**
- **So the RFEC zone exists beyond 35 mm and consider ideal location for positioning the receiver coil.**

Validation of the model in a normalized scale



- ✓ **Good agreement between the experimental and model results observed.**
- ✓ **The deviation with respect to experimental measurements is less than 10%.**

Conclusions and further works

- The RFEC characteristics in the Modified 9Cr-1Mo ferromagnetic steel was studied using COMSOL.
- The RFEC zone in this tube could be accurately identified for placing a receiver coil.
- The model was experimentally validated and deviation was found to be less than 10%.
- Further works are necessary to model the nonlinear behavior of the magnetic steel (BH characteristics)
- 3D modeling is also being explored for