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Numerical Modeling of Eddy Current Nondestructive Evaluation of Ferromagnetic Tubes via an Integral Equation Approach

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Numerical Modeling of Eddy Current Nondestructive Evaluation of Ferromagnetic Tubes via an Integral Equation Approach



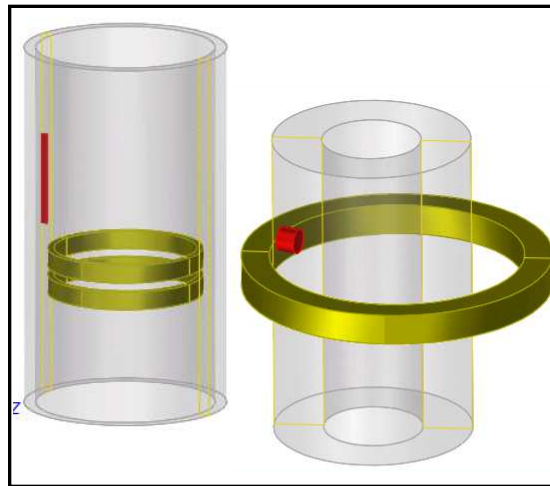
A. Skarlatos, G. Pichenot, CEA List

D. Lesselier, Marc Lambert, Bernard Duchêne L2S

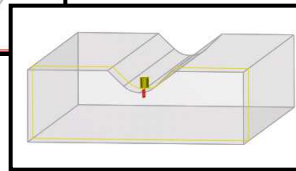
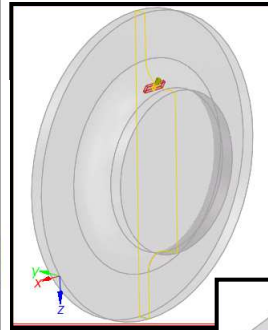
- Introduction : EC simulation and CIVA software
- Development for ferromagnetic cases
 - Integral Equation Formulation
 - Primary Field Calculation
 - Green's Dyads
 - Numerical Solution – MoM
- Validation
 - Experimental configurations
 - Finite Elements
- Additional inspection configuration studies
- Conclusion and perspectives

The CIVA Software

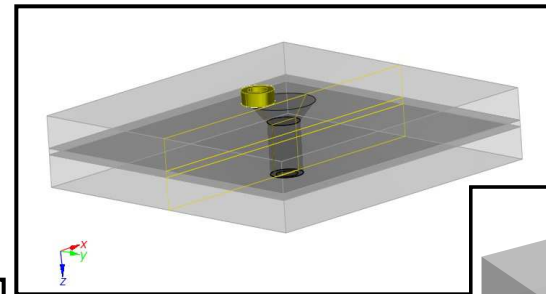
- The **CIVA** software is an expertise platform dedicated to non destructive testing.
- It is composed of simulation, imaging and analysis modules that allow to conceive or to optimize inspection techniques and to predict their performances upon realistic NDT configurations.
- **CIVA** includes **Ultrasonic (UT)** and **Eddy Current techniques (ET)**.



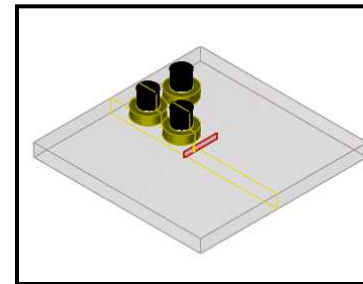
Cylindrical configurations



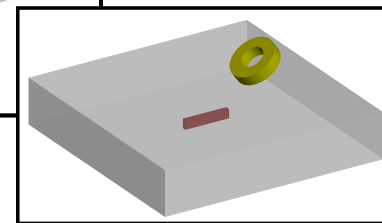
CAD defined geometries



Riveted structures



Multi-coil probes with ferrites



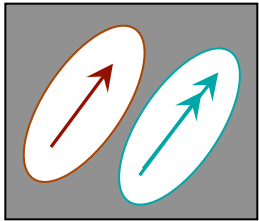
Tilted coils

- Until now the **CIVA Eddy Current** module was limited to **non-magnetic materials**.

IE Formulation

Electric Field Integral Equation (EFIE) for electric + magn. flaw

$$\vec{E}_2(\vec{r}) = \vec{E}_{\text{Tx}}^{\text{inc}}(\vec{r}) + j\omega\mu_{b_2} \int_V \overline{\overline{\mathbf{G}}}_{22}^{(ee)}(\vec{r}, \vec{r}') \cdot \delta\sigma(\vec{r}') \vec{E}_2(\vec{r}') dV' \\ + j\omega \int_V \overline{\overline{\mathbf{G}}}_{22}^{(em)}(\vec{r}, \vec{r}') \cdot \delta\mu(\vec{r}') \vec{H}_2(\vec{r}') dV'$$



Magnetic Field Integral Equation (MFIE)

$$\vec{H}_2(\vec{r}) = \vec{H}_{\text{Tx}}^{\text{inc}}(\vec{r}) + \int_V \overline{\overline{\mathbf{G}}}_{22}^{(me)}(\vec{r}, \vec{r}') \cdot \delta\sigma(\vec{r}') \vec{E}_2(\vec{r}') dV' \\ + \omega^2 \varepsilon_{b_2} \int_V \overline{\overline{\mathbf{G}}}_{22}^{(mm)}(\vec{r}, \vec{r}') \cdot \delta\mu(\vec{r}') \vec{H}_2(\vec{r}') dV'$$

Primary Field Calculation

Coaxial Coil

$$\vec{E}^{inc}(\vec{r}) = j\omega \vec{A}(\vec{r}; \vec{J})$$
$$\vec{H}^{inc}(\vec{r}) = \frac{1}{\mu_{b_2}} \nabla \times \vec{A}(\vec{r}; \vec{J})$$

Semi Analytical Solution
(Dodd –Deeds)

Off-axis Coil

$$\vec{E}^{inc}(\vec{r}) = j\omega\mu_1 \int_{coil} \overline{\overline{\mathbf{G}}}_{21}^{(ee)}(\vec{r}, \vec{r}') \cdot \vec{J}_c(\vec{r}') dV'$$
$$\vec{H}^{inc}(\vec{r}) = \frac{\mu_1}{\mu_{b_2}} \int_{coil} \overline{\overline{\mathbf{G}}}_{21}^{(me)}(\vec{r}, \vec{r}') \cdot \vec{J}_c(\vec{r}') dV'$$

- Interpolation Algorithm using Splines

Green's Dyads: Definition

Electric Source Dyads

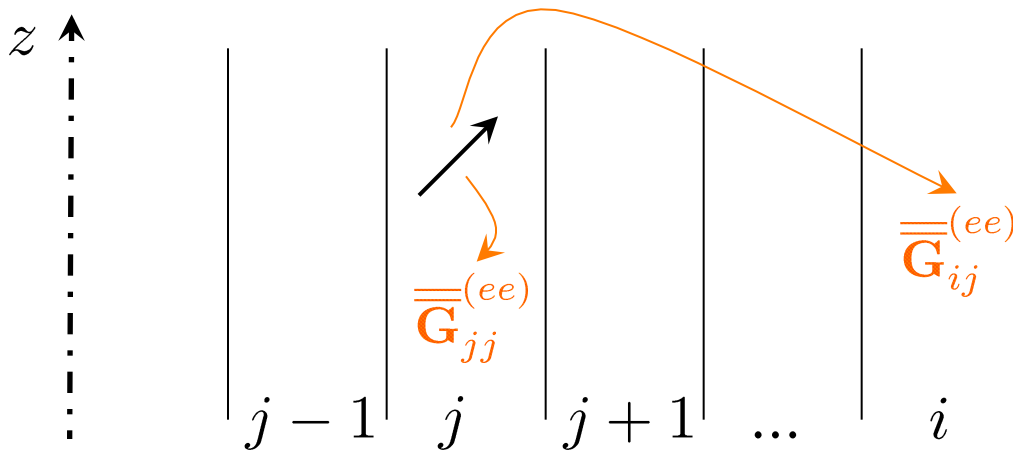
$$\nabla \times \overline{\overline{\mathbf{G}}}_{ij}^{(ee)}(\vec{r}, \vec{r}') = \overline{\overline{\mathbf{G}}}_{ij}^{(me)}(\vec{r}, \vec{r}')$$

$$\nabla \times \overline{\overline{\mathbf{G}}}_{ij}^{(me)}(\vec{r}, \vec{r}') = k_i^2 \overline{\overline{\mathbf{G}}}_{ij}^{(ee)}(\vec{r}, \vec{r}') + \delta_{ij} \overline{\overline{\mathbf{I}}} \delta(\vec{r} - \vec{r}')$$

Magnetic Source Dyads

$$\nabla \times \overline{\overline{\mathbf{G}}}_{ij}^{(em)}(\vec{r}, \vec{r}') = k_i^2 \overline{\overline{\mathbf{G}}}_{ij}^{(mm)}(\vec{r}, \vec{r}') + \delta_{ij} \overline{\overline{\mathbf{I}}} \delta(\vec{r} - \vec{r}')$$

$$\nabla \times \overline{\overline{\mathbf{G}}}_{ij}^{(mm)}(\vec{r}, \vec{r}') = \overline{\overline{\mathbf{G}}}_{ij}^{(em)}(\vec{r}, \vec{r}')$$



IE Numerical Solution: MoM

MoM System of Equations (Galerkin)

$$\begin{pmatrix} \mathbf{T}_\sigma - j\omega\mu_{2b} \hat{\mathbf{G}}_{22}^{(ee)} & \hat{\mathbf{G}}_{22}^{(em)} \\ \hat{\mathbf{G}}_{22}^{(me)} & \frac{1}{j\omega} \mathbf{T}_\mu + j\omega\tilde{\epsilon}_{2b} \hat{\mathbf{G}}_{22}^{(mm)} \end{pmatrix} \begin{pmatrix} \mathbf{J}_2 \\ \mathbf{M}_2 \end{pmatrix} = \begin{pmatrix} \mathbf{E}^{inc} \\ -\mathbf{H}^{inc} \end{pmatrix}$$

with

$$T_{\sigma_{ji}} = \int_{V_f} \frac{1}{\delta\sigma_2(\vec{r})} \vec{w}_j(\vec{r}) \cdot \vec{w}_i(\vec{r}) dV, \quad T_{\mu_{ji}} = \int_{V_f} \frac{1}{\delta\mu_2(\vec{r})} (\dots) dV,$$

$$\left[\hat{\mathbf{G}}_{22}^{(xy)} \right]_{ij} = \int_{V_f} \int_{V_f} \vec{w}_j(\vec{r}) \cdot \overline{\overline{\mathbf{G}}_{22}^{(xy)}}(\vec{r}, \vec{r}') \cdot \vec{w}_i(\vec{r}') dV' dV$$

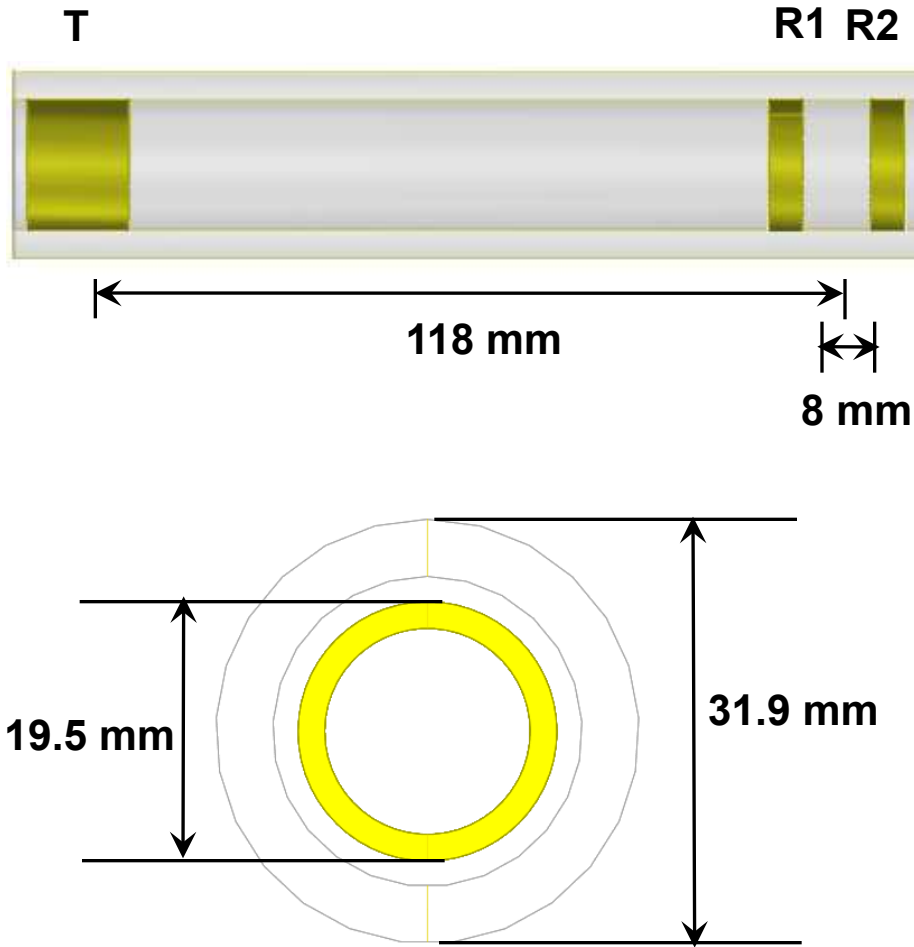
$$\text{and } E_j^{inc} = \int_{V_f} \vec{w}_j(\vec{r}) \cdot \vec{E}^{inc}(\vec{r}) dV, \quad H_j^{inc} = \int_{V_f} \vec{w}_j(\vec{r}) \cdot \vec{H}^{inc}(\vec{r}) dV$$

Variation of the probe mutual impedance

$$\Delta Z = -\frac{1}{I_1 I_2} \int_{V_f} \left[\vec{E}_{\text{Rx}}^{inc}(\vec{r}') \cdot \vec{J}_2(\vec{r}') - \vec{H}_{\text{Rx}}^{inc}(\vec{r}') \cdot \vec{M}_2(\vec{r}') \right] dV'$$

Validation: Remote Field Probe

- Probe Layout (RFEC Probe)



- Probe Parameters

$$\rho_{c_{in}} = 7.75 \text{ mm}, \rho_{c_{out}} = 9.75 \text{ mm}$$

$$h_T = 15 \text{ mm}, h_R = 5 \text{ mm}$$

$$N_T = 2700, N_R = 900 \text{ (turns)}$$

$$f = 150 \text{ Hz}$$

Connection:

Receivers: Differential

- Tube Parameters

$$\rho_{in} = 11.66 \text{ mm},$$

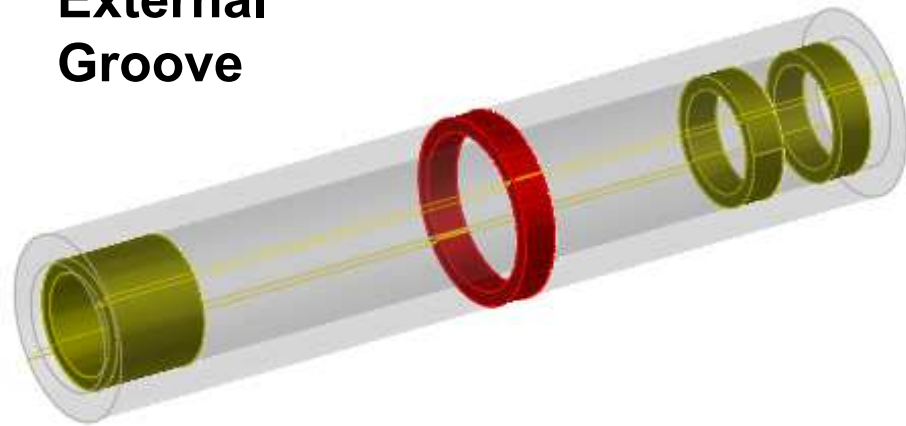
$$\rho_{out} = 15.95 \text{ mm}$$

$$\sigma_t = 3.5 \text{ MS/m}, \mu_{t_r} = 100$$

$$\text{Skin depth: } \delta = 2.7 \text{ mm}$$

Validation: 2D Flaw

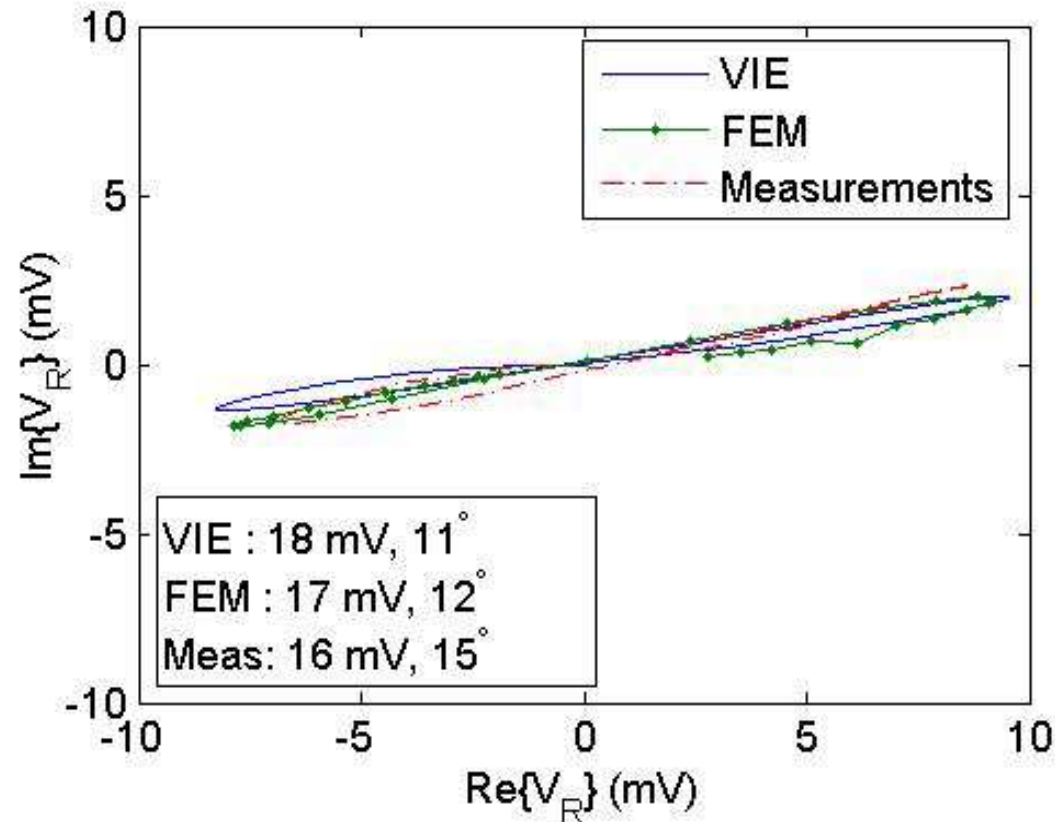
External Groove



- Flaw Parameters
50% (tube thickness)
 $h_f = 5$ mm

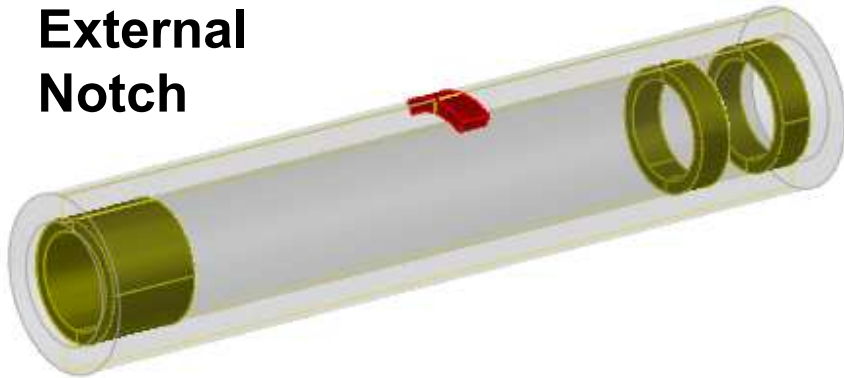
Reference:

1. Z. Chen, M. Rebican, K. Miya, and T. Takagi, "Three-dimensional simulation of remote field ECT using the Ar method and a new formula for signal calculation", Res. in Nondestr. Eval, vol. 16, pp. 35-53, 2005
2. M. Rebican, Z. Chen, N. Yusa, K. Miya, T. Uchimoto, and T. Takagi, "Investigation of numerical precision of 3-D RFECT signal simulations", IEEE Trans. Magn., vol. 41, no 5, pp. 1968-1971, 2005.

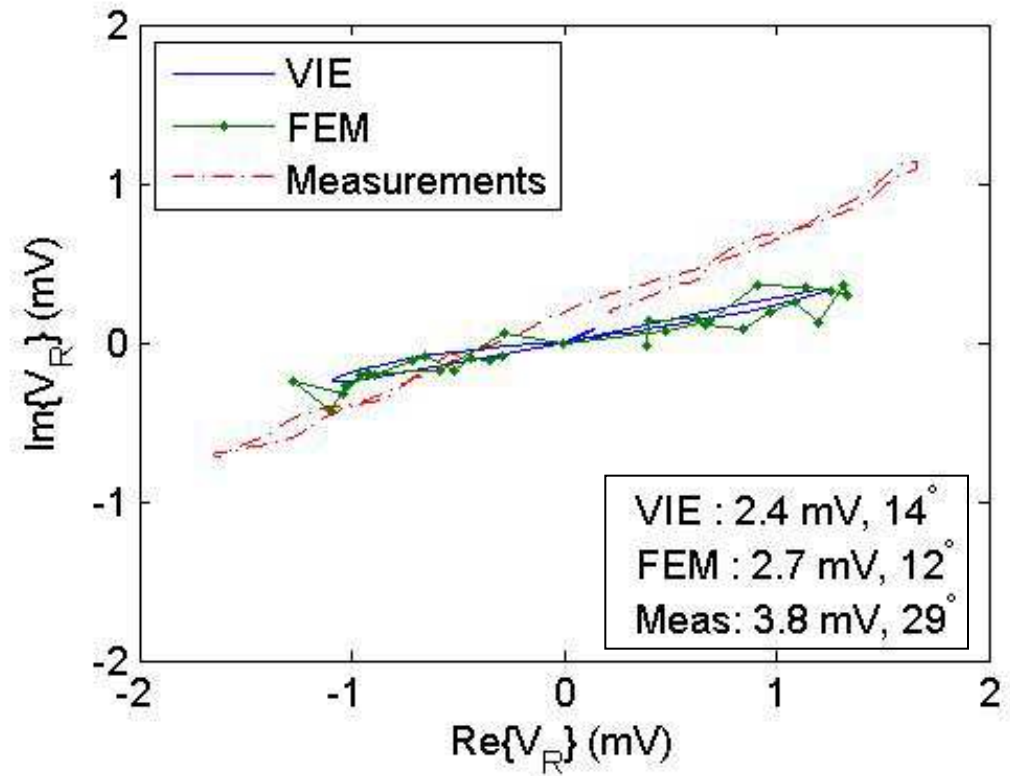


Validation: 3D Flaw

External Notch



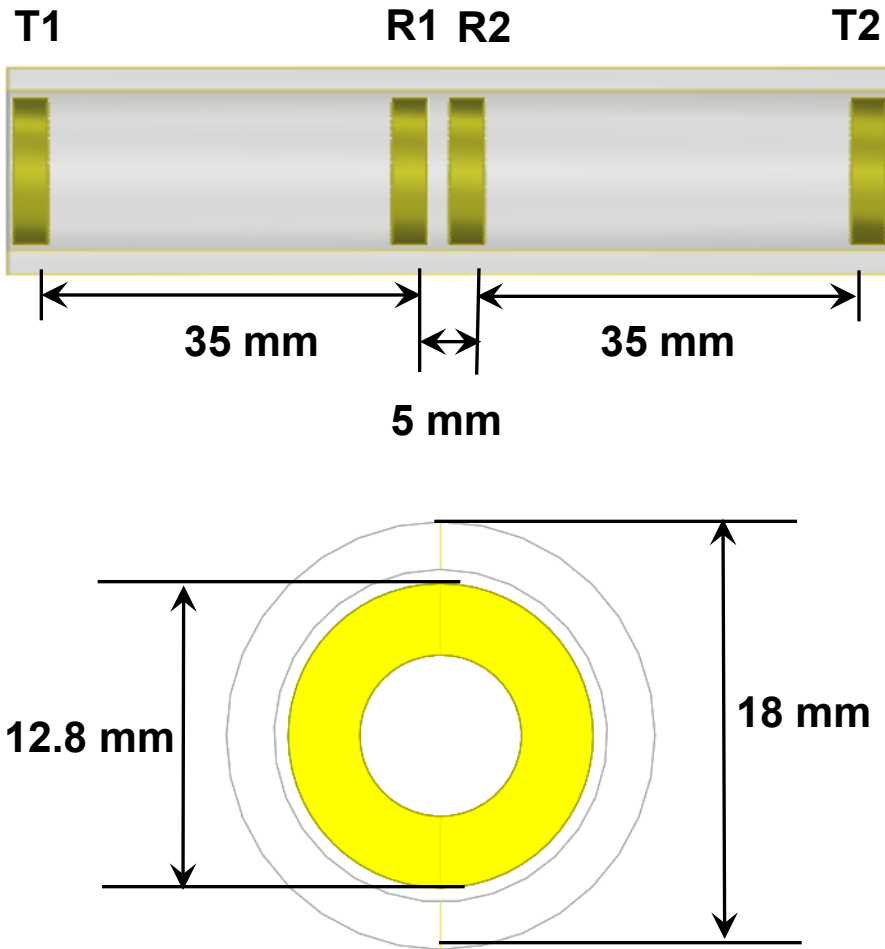
- Flaw Parameters
50% (tube thickness)
 $h_f = 5 \text{ mm}$, $\theta = 60^\circ$



- Good agreement between VIE and FEM results
- Discrepancies with experimental data

Validation: Remote Field Probe

- Probe Layout (RFEC Probe)



- Probe Parameters

$$\rho_{c_{in}} = 3.4 \text{ mm}, \rho_{c_{out}} = 6.4 \text{ mm}$$

$$h = 3 \text{ mm}$$

$$N_{T_x} = 150, N_{R_x} = 1531 \text{ (turns)}$$

$$f = 250 \text{ Hz}$$

Connection:

Driving Coils: In Phase

Receivers: Differential

- Tube Parameters

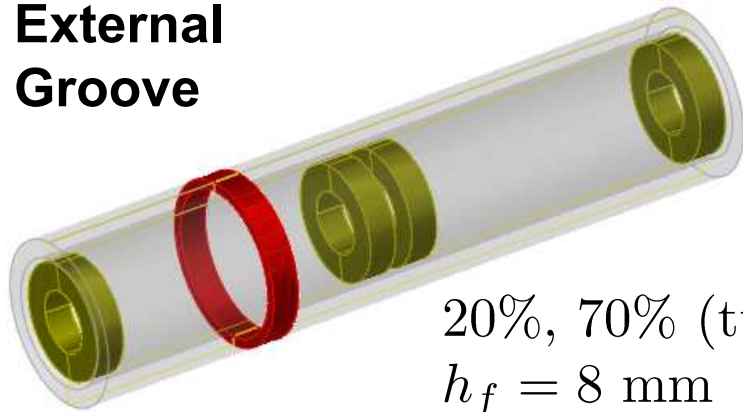
$$\rho_{in} = 7 \text{ mm}, \rho_{out} = 9 \text{ mm}$$

$$\sigma_t = 6.25 \text{ MS/m}, \mu_{t_r} = 210$$

$$\text{Skin depth: } \delta = 0.88 \text{ mm}$$

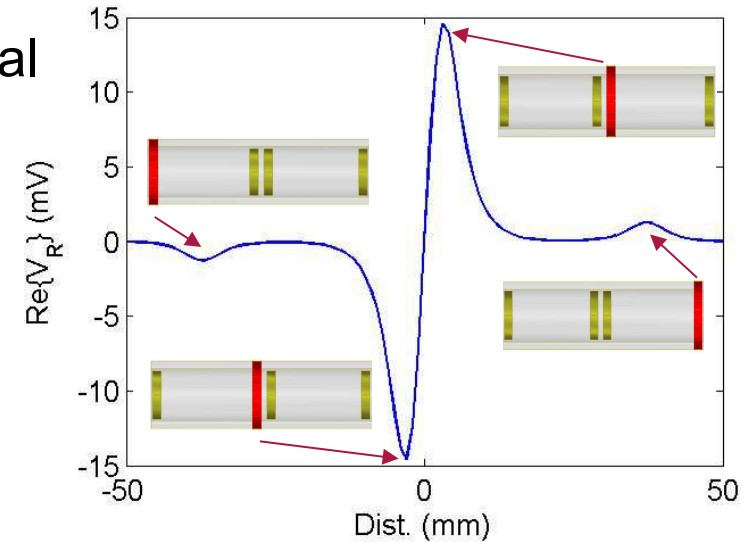
Validation: 2D Flaw

External Groove

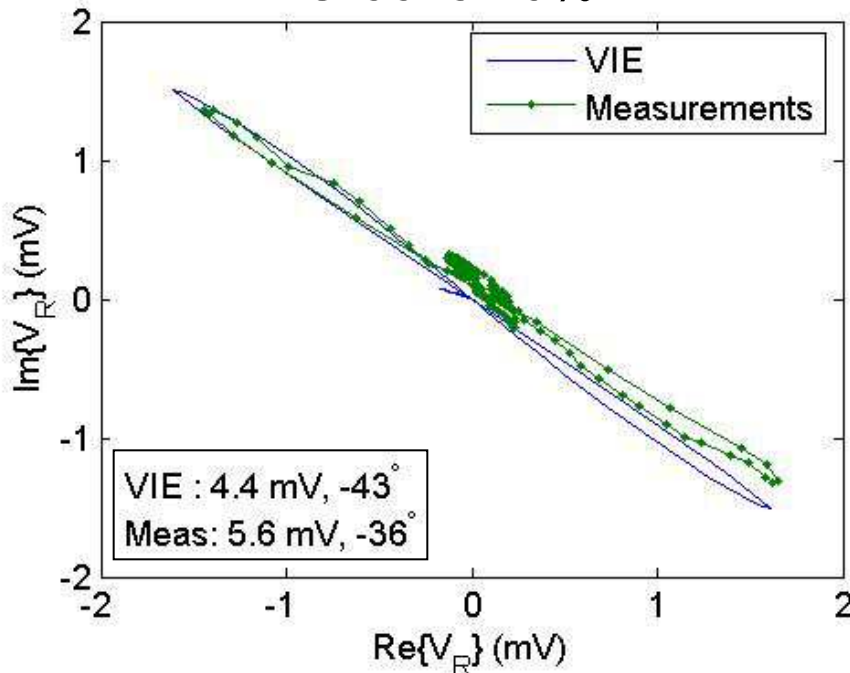


20%, 70% (tube thickness)
 $h_f = 8$ mm

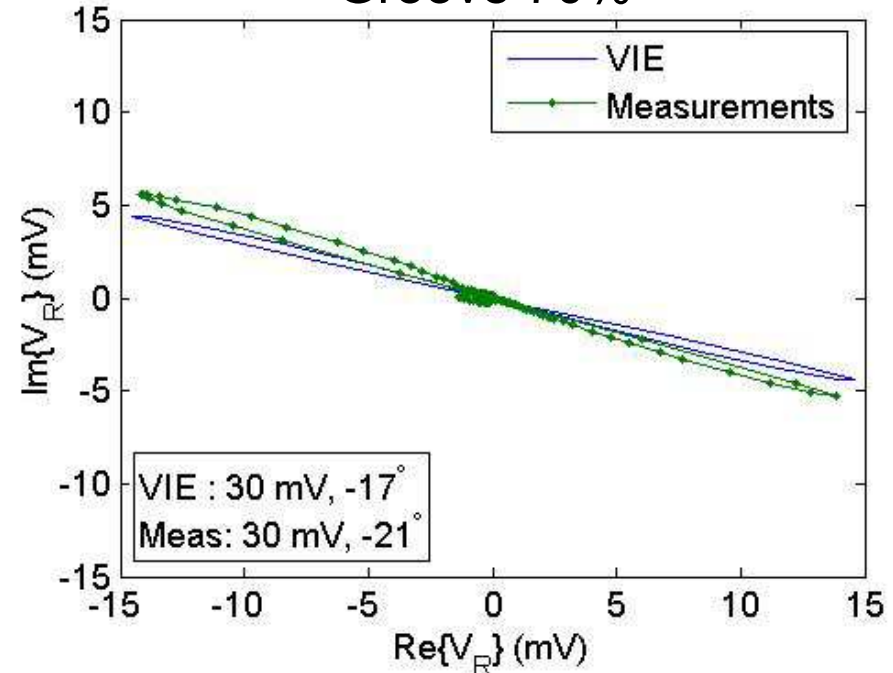
Probe Signal (Simulation)



Groove 20%

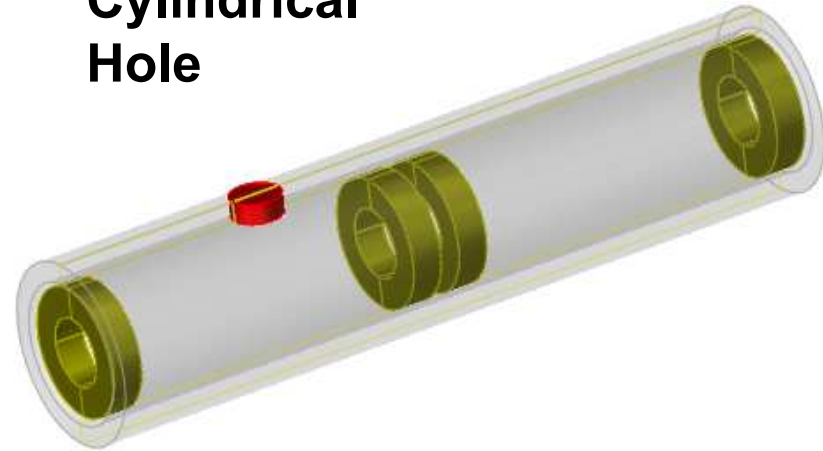


Groove 70%



Validation: 3D Flaw

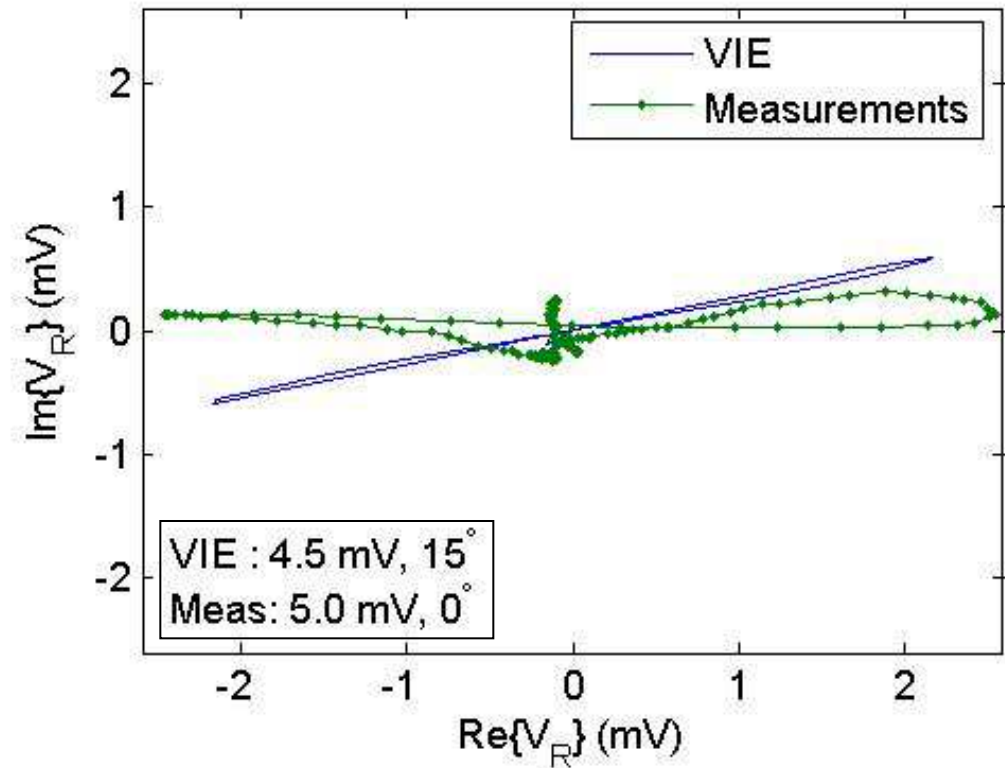
Cylindrical Hole



- Hole Dimensions
100%, $D = 5$ mm

- Fabrication Effects

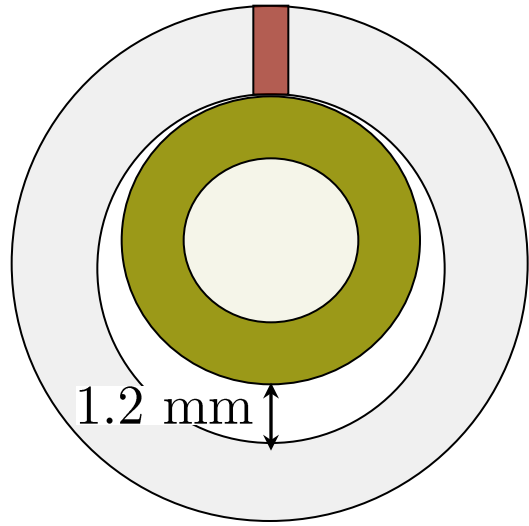
Flaw Fabrication	
Electro-erosion	$5 \angle 0^\circ$ mV
Mech. Drilling	$4.2 \angle 6^\circ$ mV



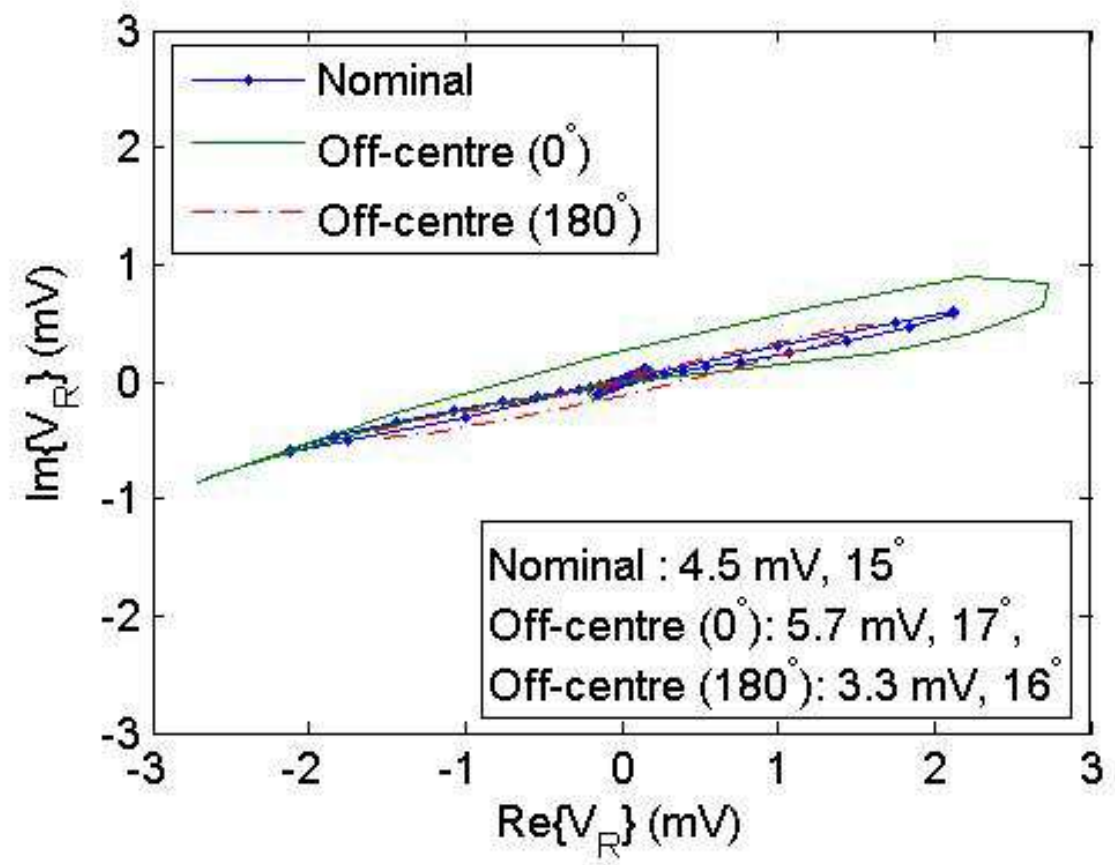
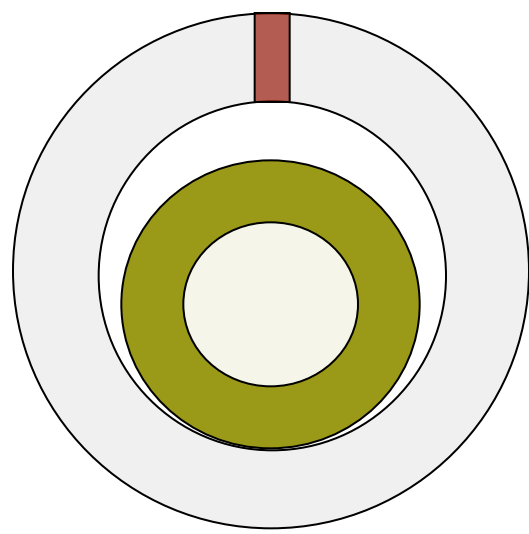
- Same behavior with the previous 3D case
- Probably due to flaw fabrication side effects

Off-centering Effect in Case of a Hole

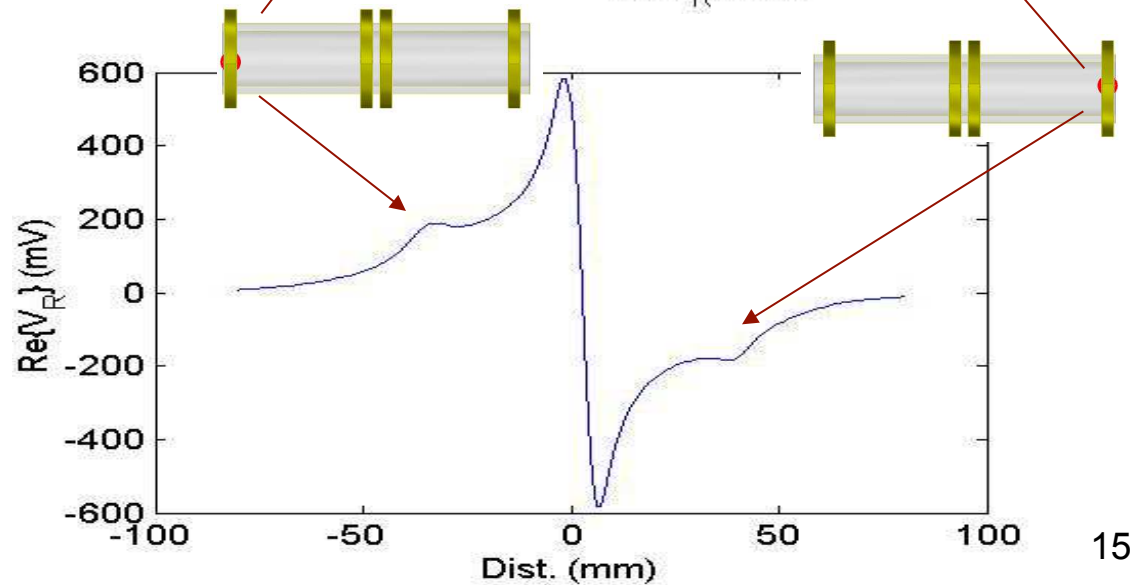
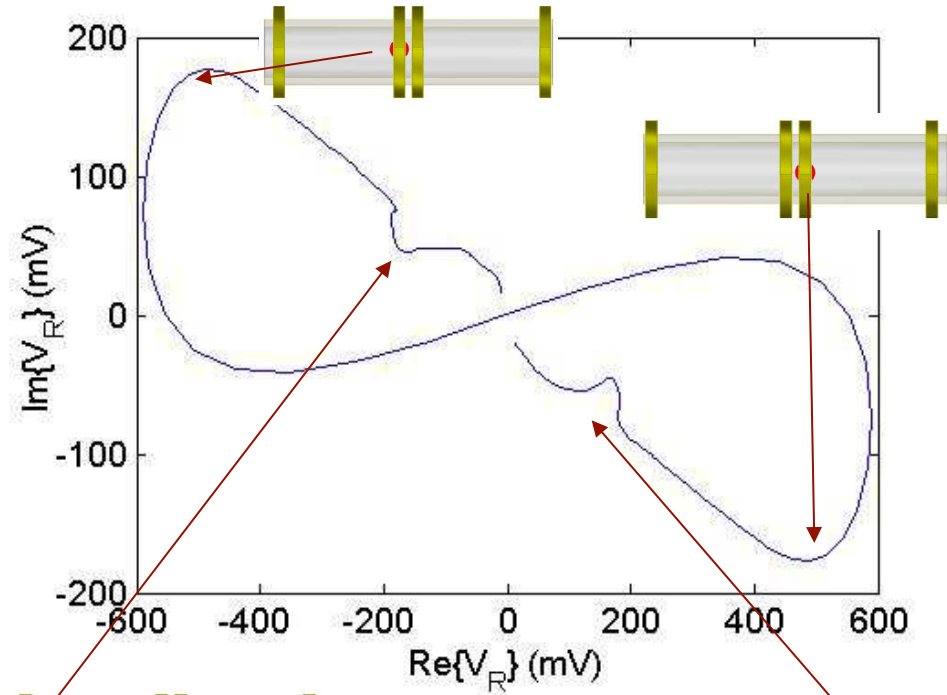
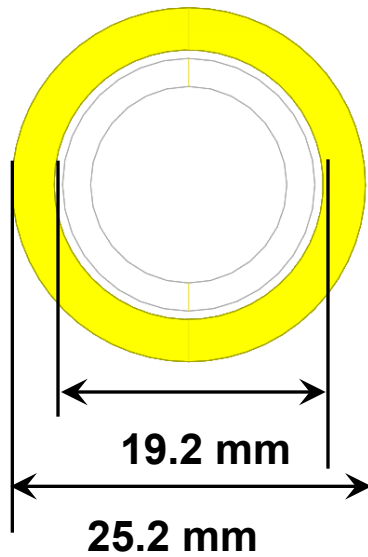
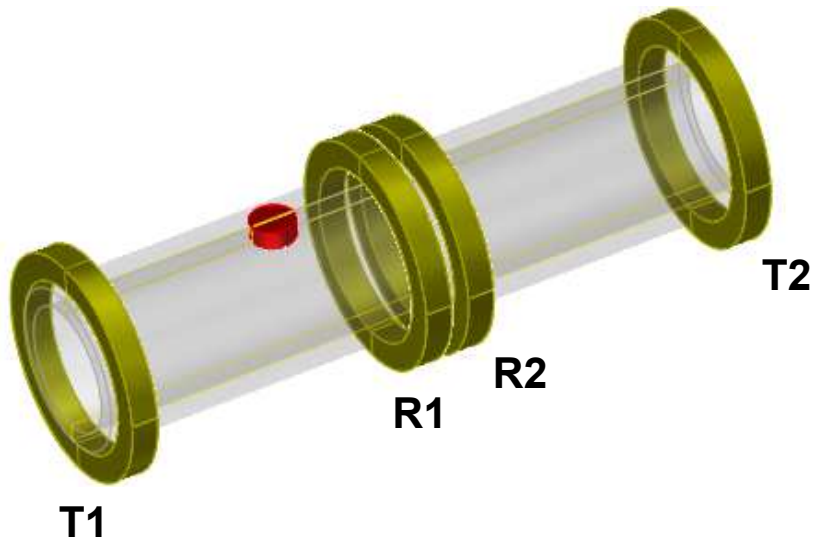
Off-centre (0°)



Off-centre (180°)



Inspection with External Probe



- NDE of Ferromagnetic Tubes
- Modeling via the Integral Equation Approach
 - Fast: $\sim 1/2$ to 1 h for ~ 300 probe positions
- Good agreement with experimental results
- Integrated in CIVA - available with the next release (9.0)

Perspectives

- Extension of the existing models to treat
 - Planar multilayered ferromagnetic configurations
 - Tubes with support plates (nuclear applications)
 - Tubes in expanded zone (nuclear applications)
 - Ferromagnetic tubing inspection with surface ridding probes

