



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

Anastassios Skarlatos, Grégoire Pichenot, Dominique Lesselier, Marc Lambert, Bernard Duchêne

► To cite this version:

Anastassios Skarlatos, Grégoire Pichenot, Dominique Lesselier, Marc Lambert, Bernard Duchêne. Numerical Modeling of Eddy Current Nondestructive Evaluation of Ferromagnetic Tubes via an Integral Equation Approach. ENDE'07, Jun 2007, Cardiff, United Kingdom. hal-01107465

HAL Id: hal-01107465

<https://centralesupelec.hal.science/hal-01107465>

Submitted on 20 Jan 2015

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

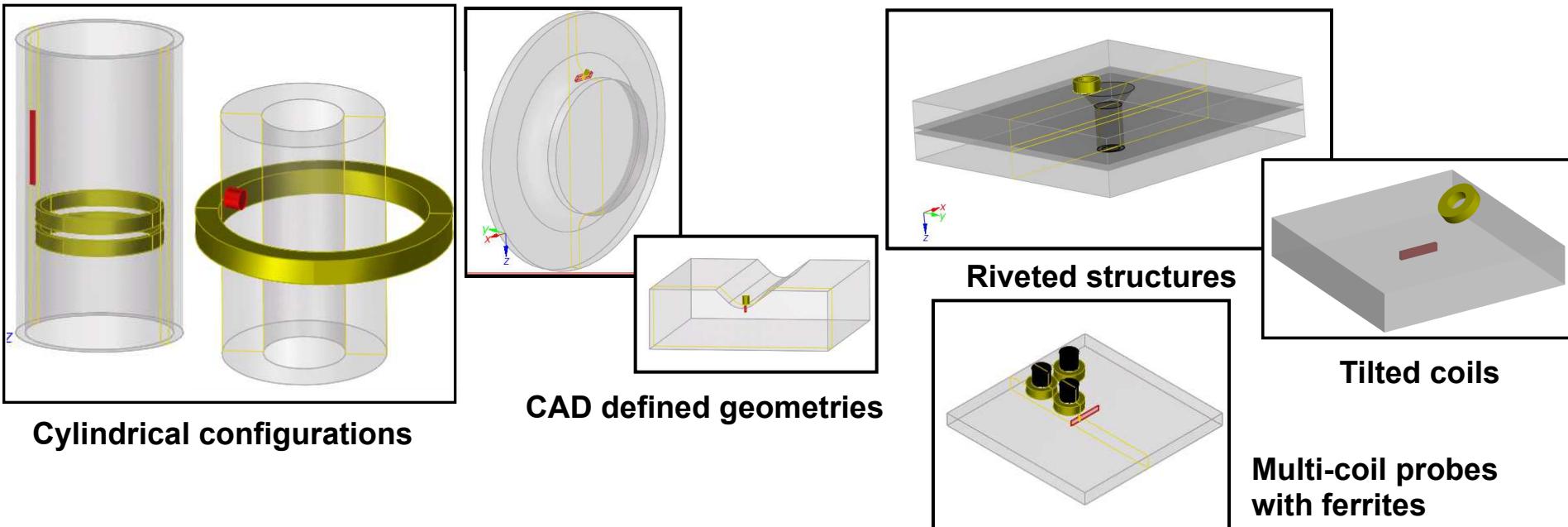
Numerical Modeling of Eddy Current Nondestructive Evaluation of Ferromagnetic Tubes via an Integral Equation Approach

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**).

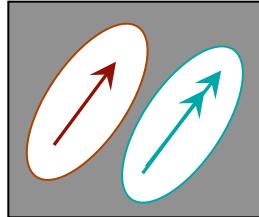


- Until now the **CIVA Eddy Current** module was limited to **non-magnetic materials**.

IE Formulation

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

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



Magnetic Field Integral Equation (MFIE)

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

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

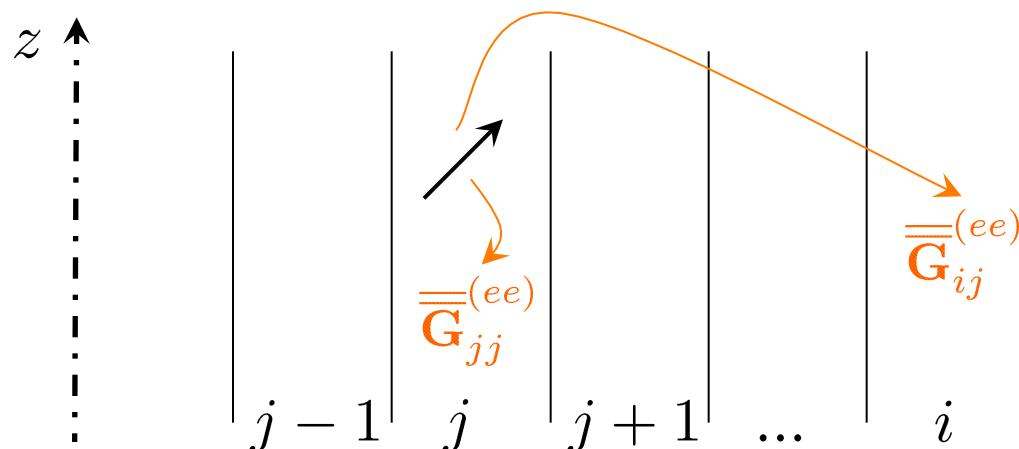
$$\nabla \times \overline{\overline{\mathbf{G}}}^{(ee)}_{ij} (\vec{r}, \vec{r}') = \overline{\overline{\mathbf{G}}}^{(me)}_{ij} (\vec{r}, \vec{r}')$$

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

Magnetic Source Dyads

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

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



IE Numerical Solution: MoM

MoM System of Equations (Galerkin)

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

with

Unknowns **Primary Field**

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

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

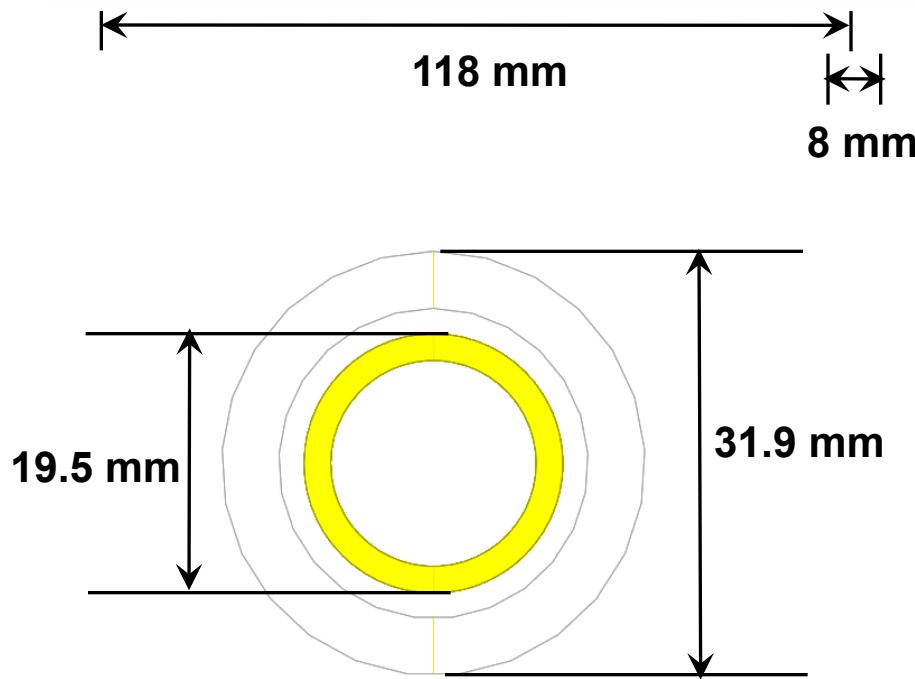
$$\text{and } E_j^{inc} = \int_{V_f} \vec{w}_j(\vec{r}) \cdot \vec{E}^{inc}(\vec{r}) dV, \quad H_j^{inc} = \int_{V_f} \vec{w}_j(\vec{r}) \cdot \vec{H}^{inc}(\vec{r}) dV$$

Variation of the probe mutual impedance

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

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

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

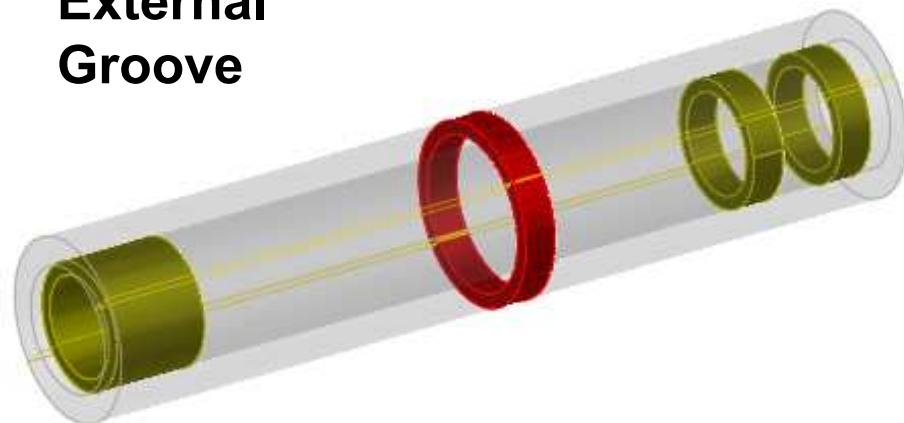
$$\rho_{out} = 15.95 \text{ mm}$$

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

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

Validation: 2D Flaw

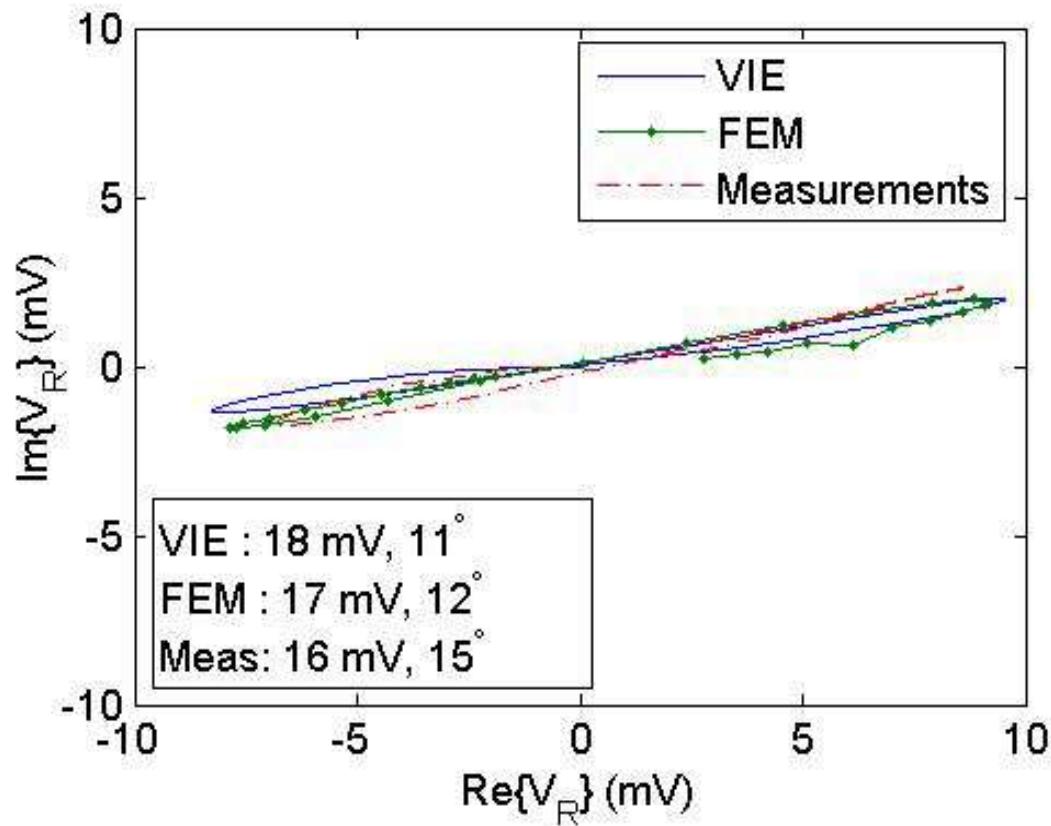
External Groove



- Flaw Parameters

50% (tube thickness)

$$h_f = 5 \text{ mm}$$

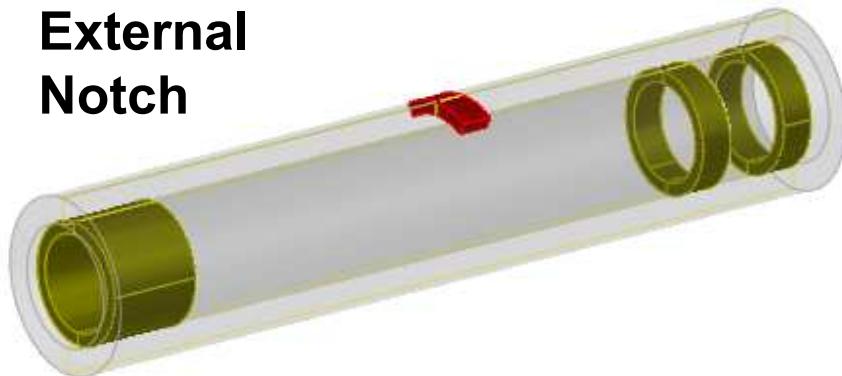


Reference:

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

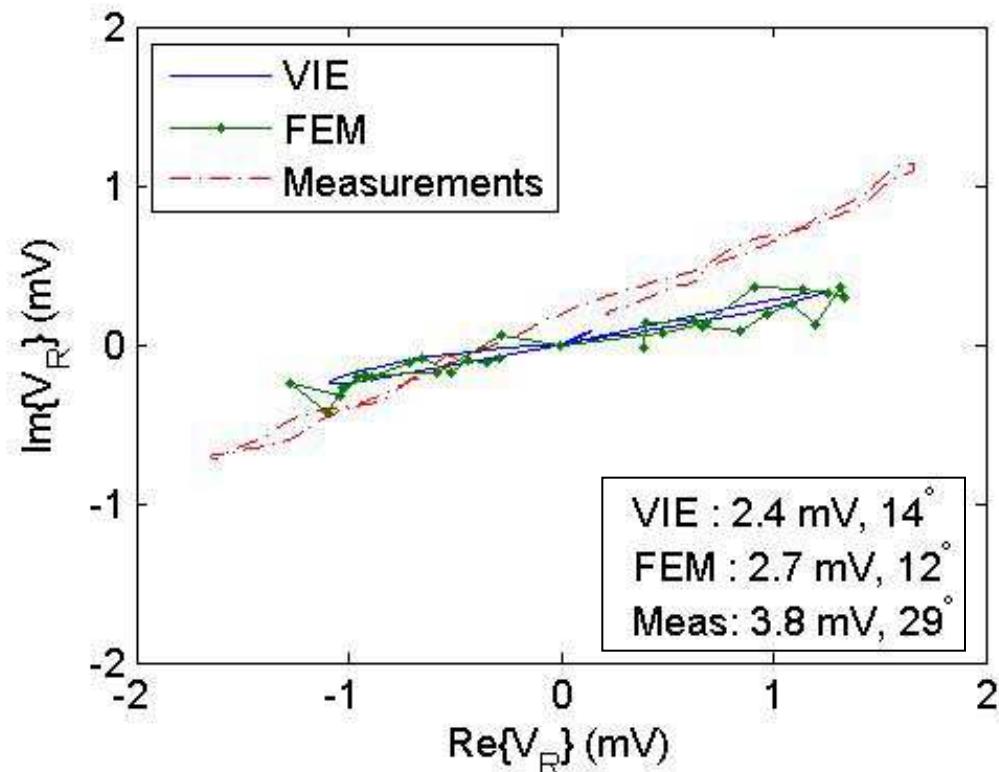
External
Notch



- Flaw Parameters

50% (tube thickness)

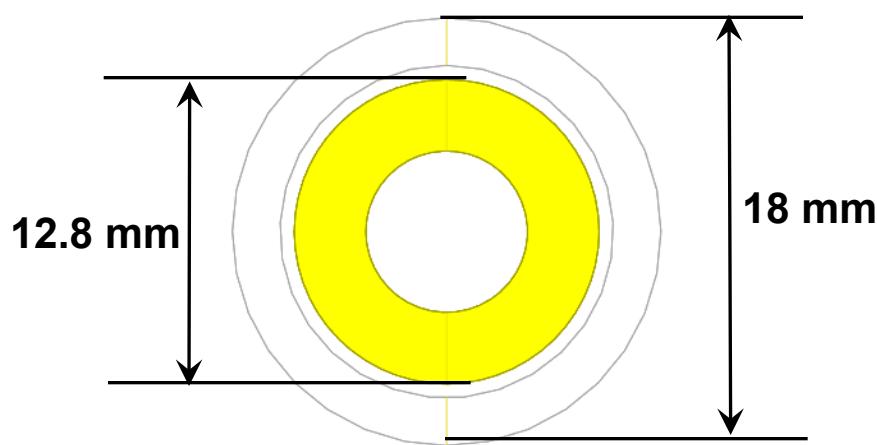
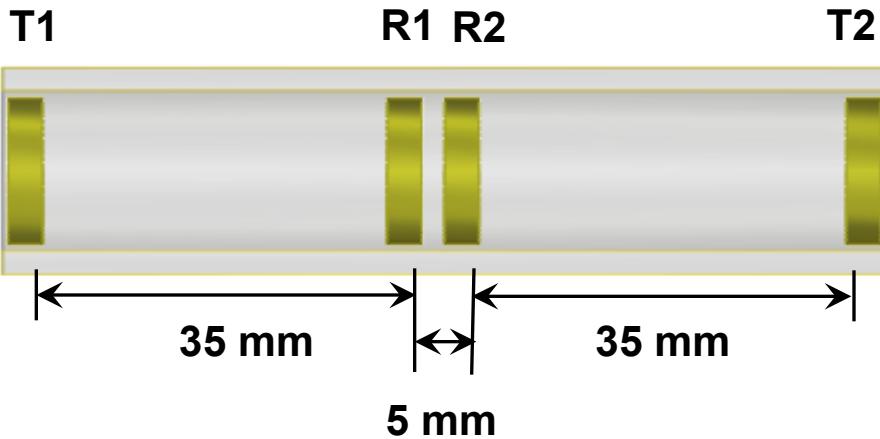
$$h_f = 5 \text{ mm}, \theta = 60^\circ$$



- 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

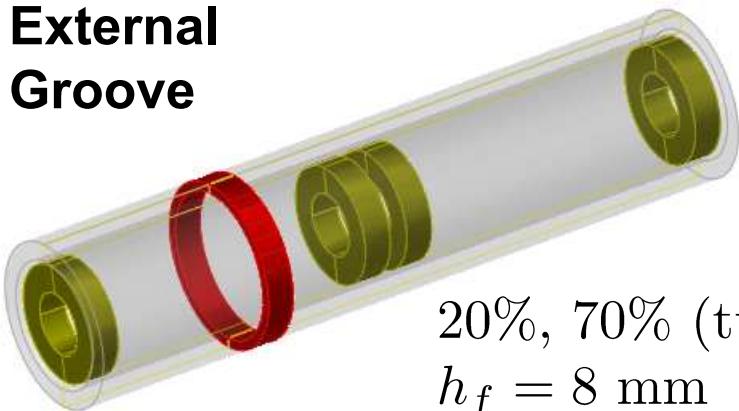
$$\rho_{in} = 7 \text{ mm}, \rho_{out} = 9 \text{ mm}$$

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

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

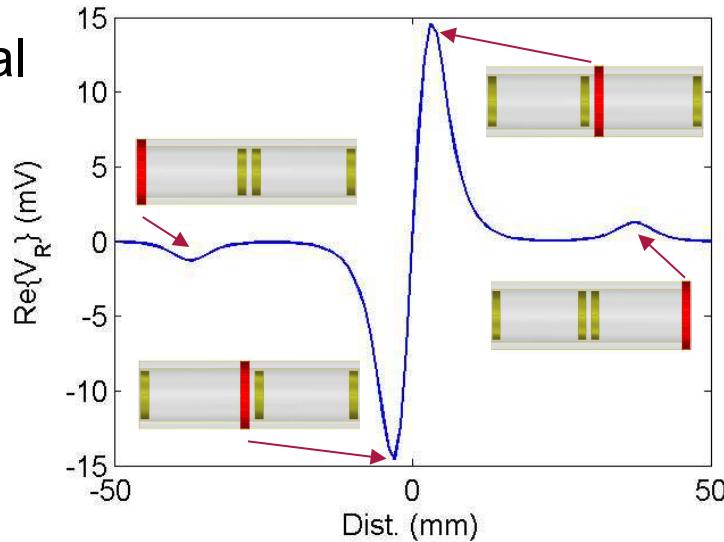
Validation: 2D Flaw

External Groove

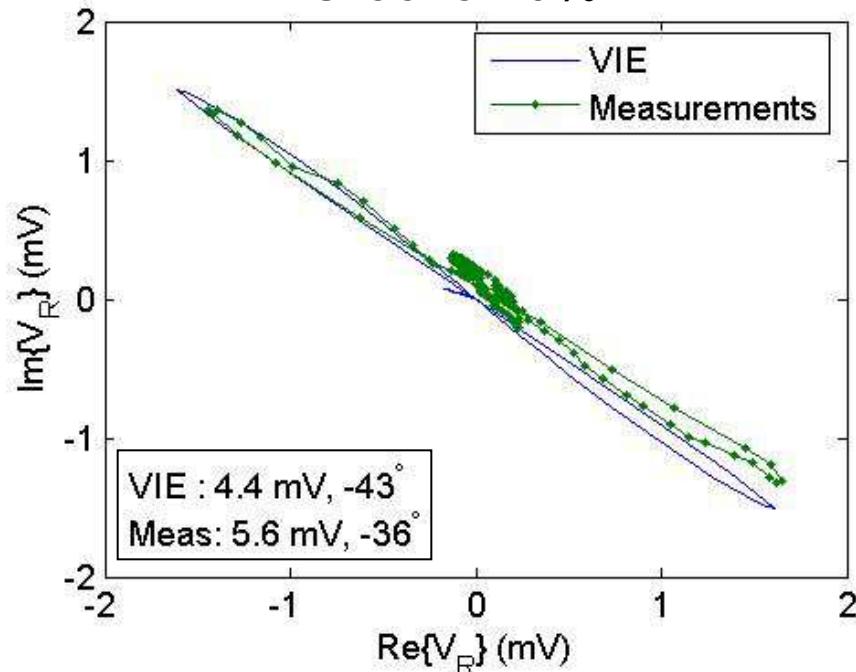


20%, 70% (tube thickness)
 $h_f = 8 \text{ mm}$

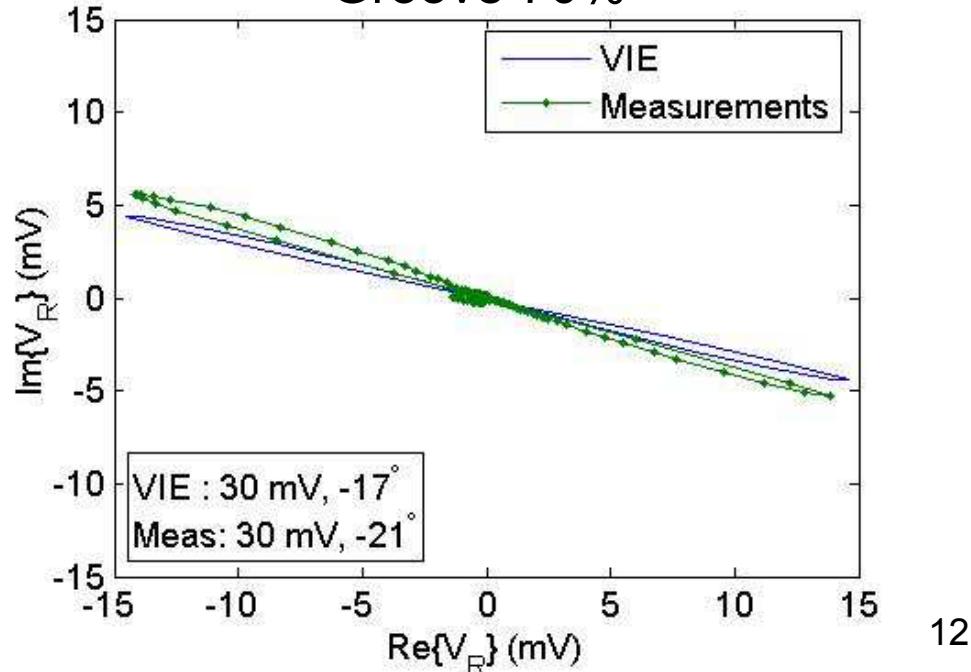
Probe Signal (Simulation)



Groove 20%

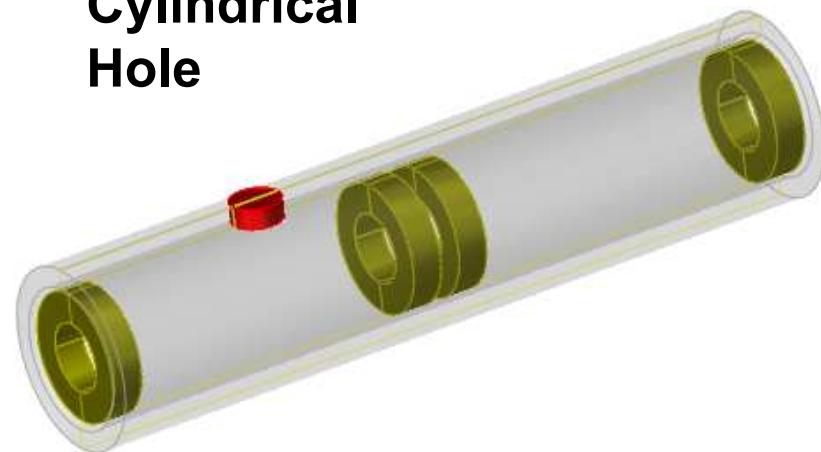


Groove 70%



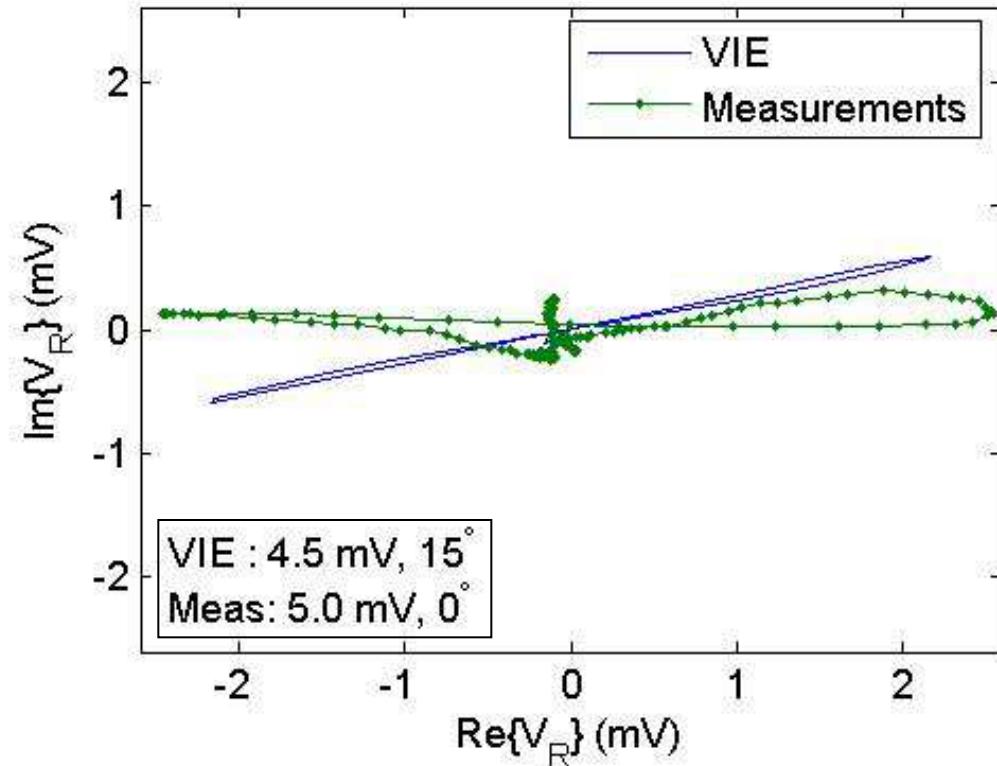
Validation: 3D Flaw

Cylindrical Hole



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

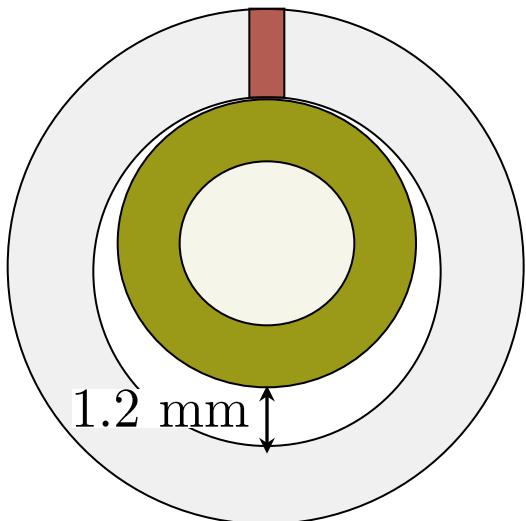
Flaw Fabrication	
Electro-erosion	$5 \angle 0^\circ$ mV
Mech. Drilling	$4.2 \angle 6^\circ$ mV



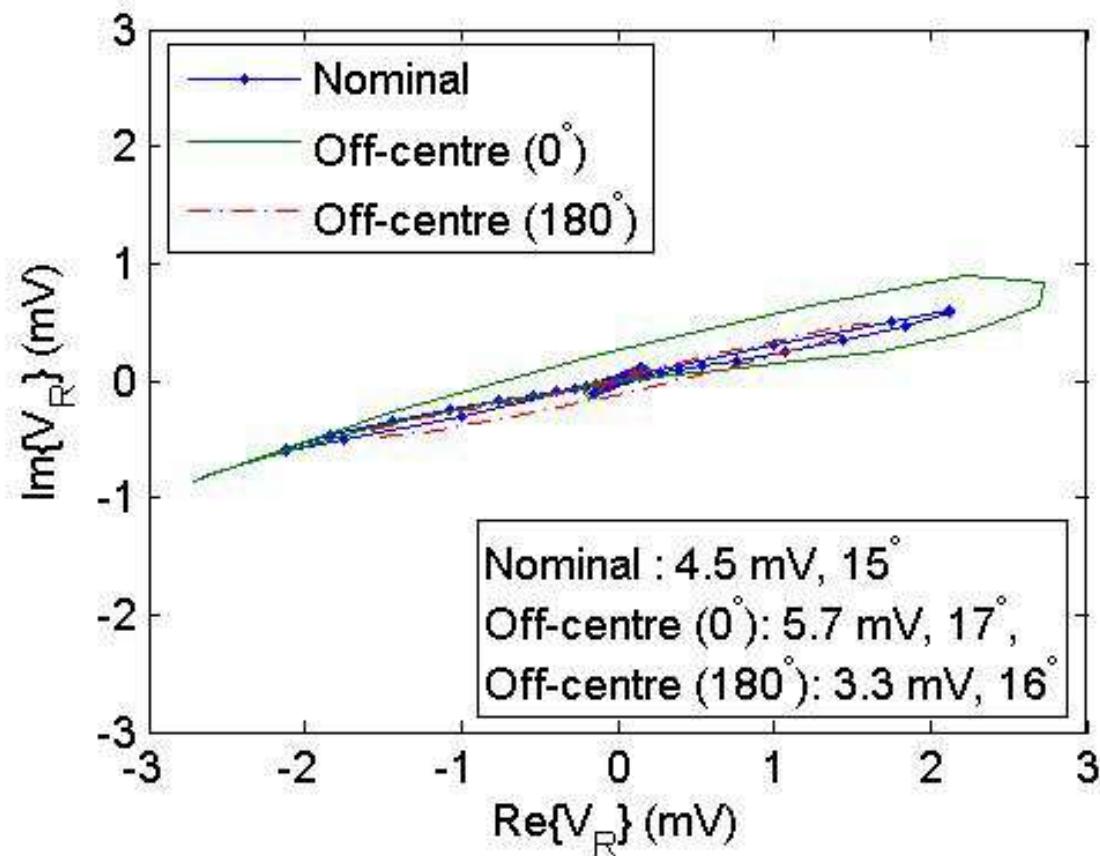
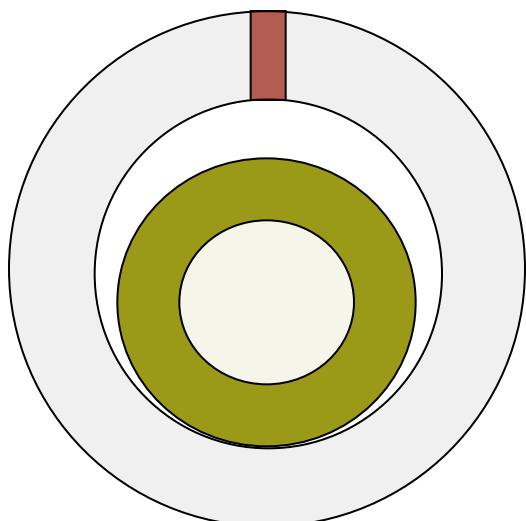
- Same behavior with the previous 3D case
- Probably due to flaw fabrication side effects

Off-centering Effect in Case of a Hole

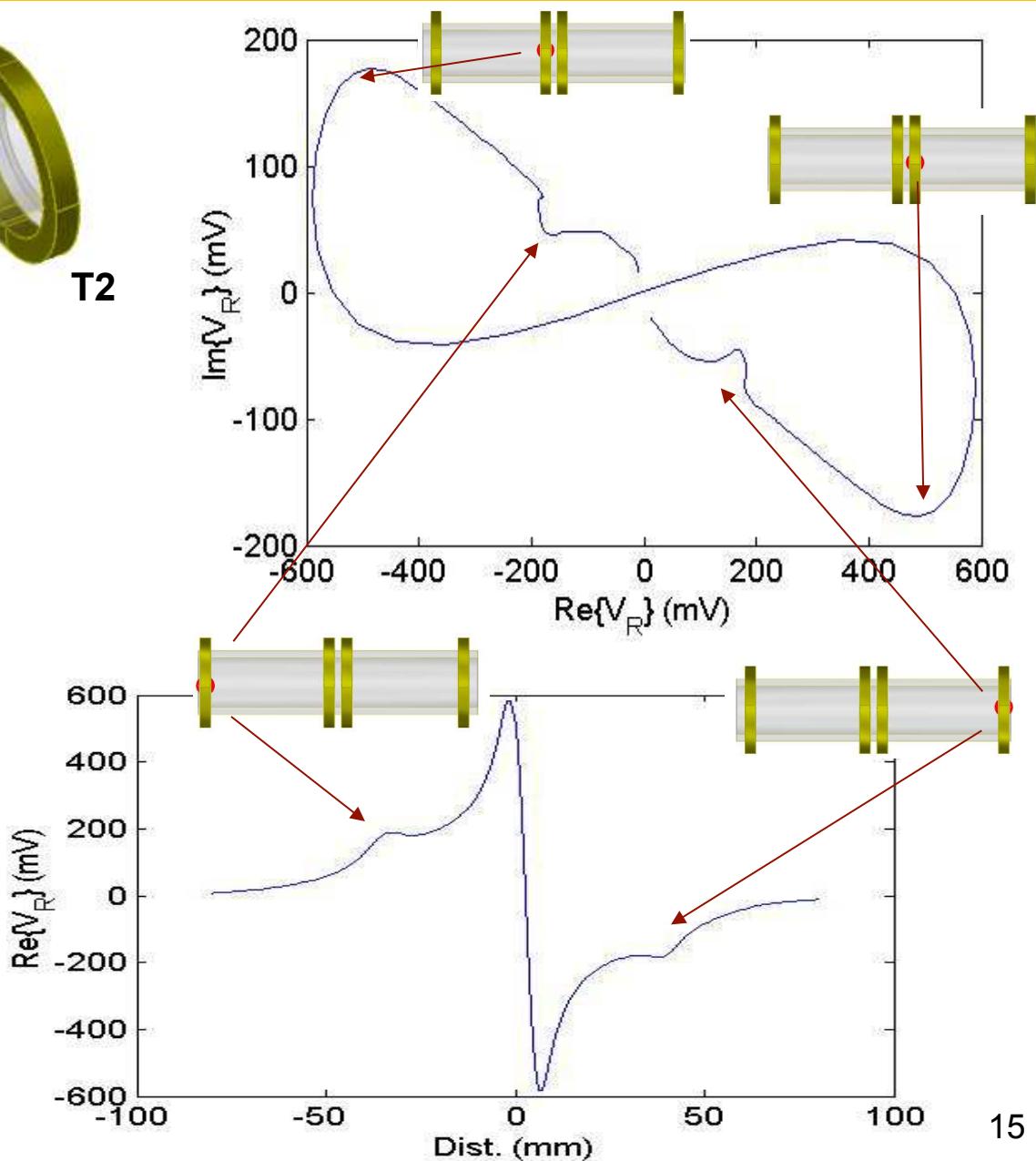
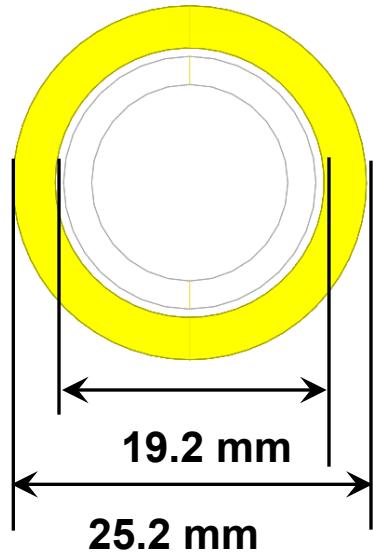
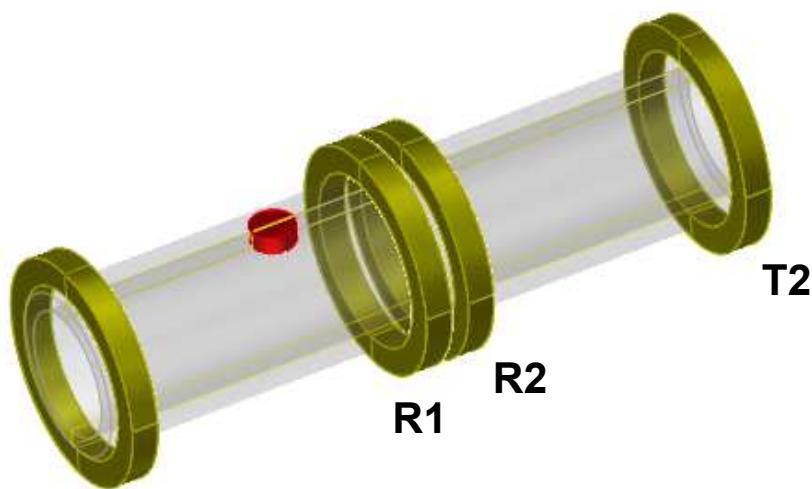
Off-centre (0°)



Off-centre (180°)



Inspection with External Probe



Conclusion

- NDE of Ferromagnetic Tubes
- Modeling via the Integral Equation Approach

Fast: ~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

μ_1
μ_2
μ_3

