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

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A. Skarlatos, G. Pichenot, CEA List

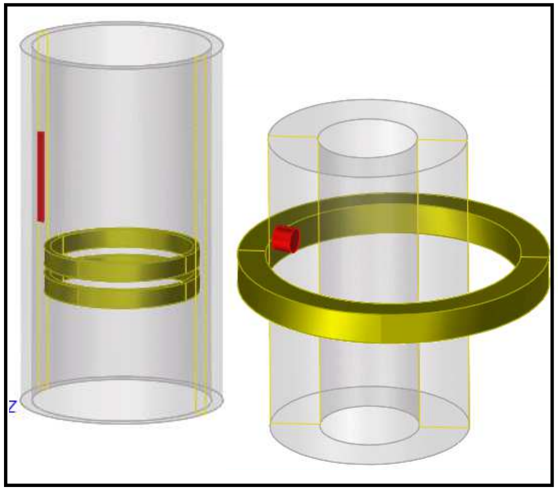
D. Lesselier, Marc Lambert, Bernard Duchêne L2S

Outline

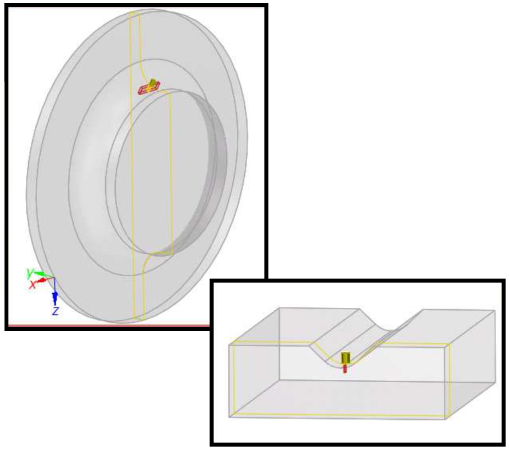
- Introduction : EC simulation and CIVA software
- Development for ferromagnetic cases
  - Integral Equation Formulation
  - Primary Field Calculation
  - Green's Dyads
  - Numerical Solution – MoM
- Validation
  - Experimental configurations
  - Finite Elements
- Additional inspection configuration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

The CIVA Software

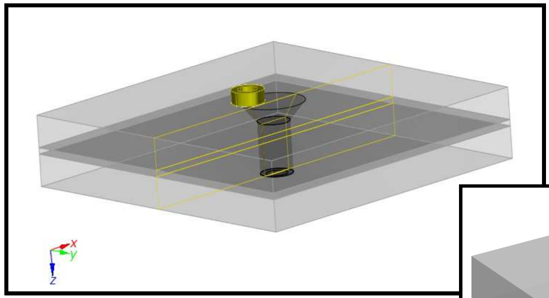
- The **CIVA** software is an expertise platform dedicated to non destructive testing.
- It is composed of simulation, imaging and analysis modules that allow to conceive or to optimize inspection techniques and to predict their performances upon realistic NDT configurations.
- **CIVA** includes **Ultrasonic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



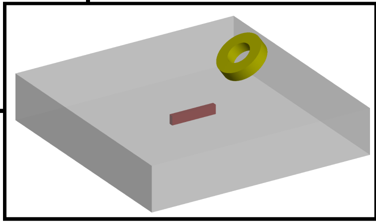
Cylindrical configurations



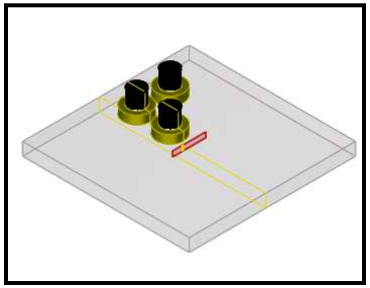
CAD defined geometries



Riveted structures



Tilted coils



Multi-coil probes with ferrites

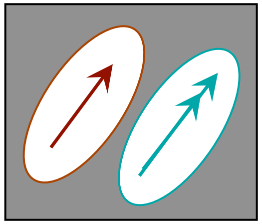
- Until now the **CIVA Eddy Current** module was limited to **non-magnetic materials**.

IE Formulation

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

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

$$+j\omega\int\limits_V \overline{\overline{\mathbf{G}}}^{(em)}_{22}(\vec{r},\vec{r}\,')\cdot\boxed{\delta\mu(\vec{r}\,')\,\vec{H}_2(\vec{r}\,')}\,dV'$$



Magnetic Field Integral Equation (MFIE)

$$\vec{H}_2(\vec{r}) = \vec{H}^{inc}_{\mathrm{Tx}}(\vec{r}) + \int\limits_V \overline{\overline{\mathbf{G}}}^{(me)}_{22}(\vec{r},\vec{r}\,')\cdot\delta\sigma(\vec{r}\,')\,\vec{E}_2(\vec{r}\,')\,dV'$$

$$+\omega^2\varepsilon_{b_2}\int\limits_V \overline{\overline{\mathbf{G}}}^{(mm)}_{22}(\vec{r},\vec{r}\,')\cdot\delta\mu(\vec{r}\,')\,\vec{H}_2(\vec{r}\,')\,dV'$$

Primary Field Calculation

Coaxial Coil

$$\vec{E}^{inc}(\vec{r}) = j\omega\vec{A}\left(\vec{r};\vec{J}\right)$$

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

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

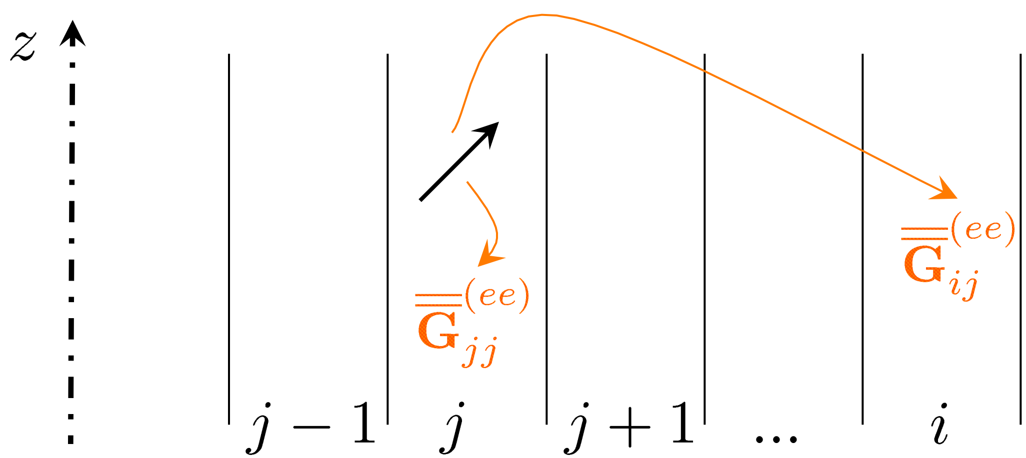
$$\nabla \times \overline{\overline{\mathbf{G}}}_{ij}^{(ee)}(\vec{r},\vec{r}\,') = \overline{\overline{\mathbf{G}}}_{ij}^{(me)}(\vec{r},\vec{r}\,')$$

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

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)

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

Unknowns Primary Field

with

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

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

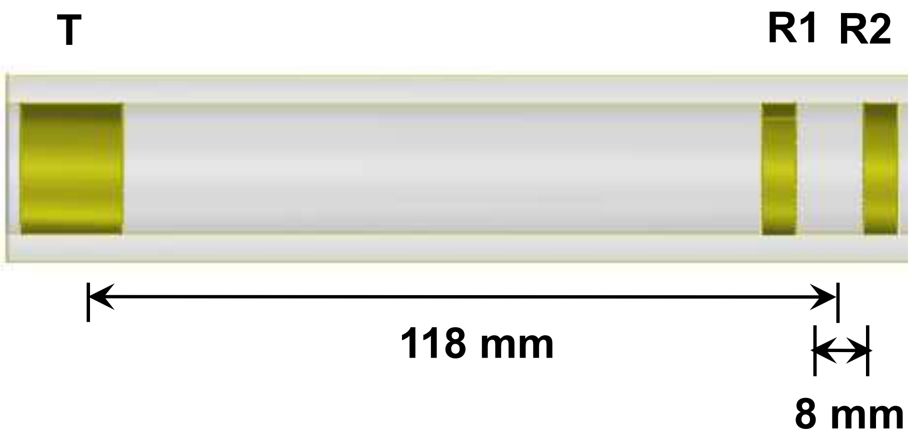
and $E_j^{inc} = \int\limits_{V_f} \vec{w}_j(\vec{r}) \cdot \vec{E}^{inc}(\vec{r})\, dV, \; H_j^{inc} = \int\limits_{V_f} \vec{w}_j(\vec{r}) \cdot \vec{H}^{inc}(\vec{r})\, dV$

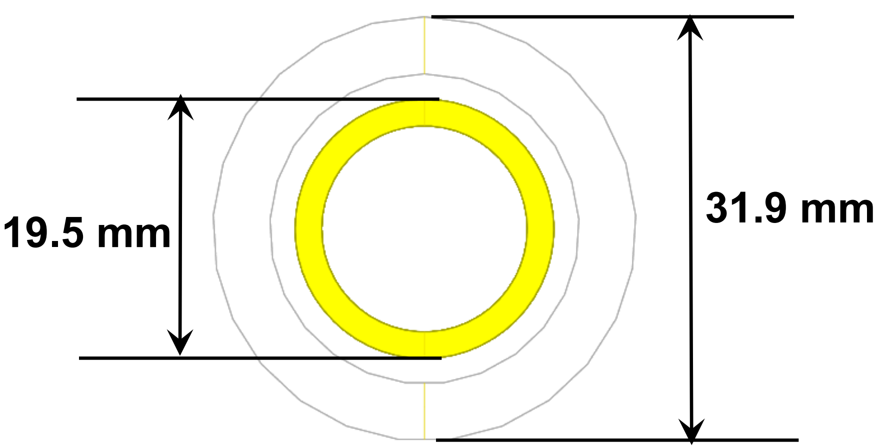
Variation of the probe mutual impedance

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

Validation: Remote Field Probe

- Probe Layout (RFEC Probe)





- Probe Parameters

$\rho_{c_{in}} = 7.75$ mm, $\rho_{c_{out}} = 9.75$ mm
$h_T = 15$ mm, $h_R = 5$ mm
$N_T = 2700$, $N_R = 900$ (turns)

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

Connection:
Receivers: Differential

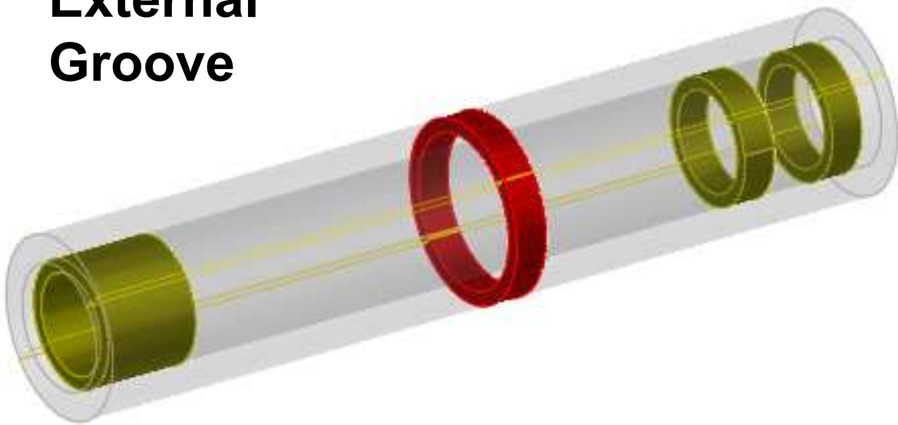
- Tube Parameters

$\rho_{in} = 11.66$ mm,
$\rho_{out} = 15.95$ mm
$\sigma_t = 3.5$ MS/m, $\mu_{t_r} = 100$

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

Validation: 2D Flaw

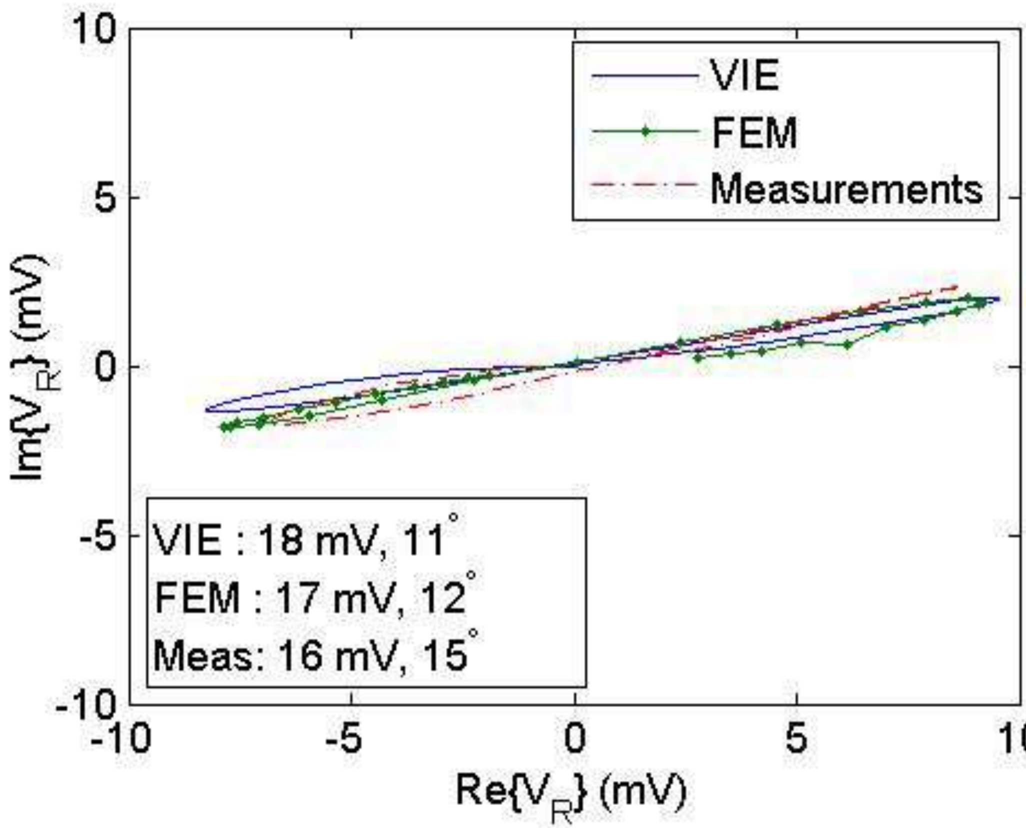
External Groove



- Flaw Parameters

  50% (tube thickness)

  $h_f = 5$ mm

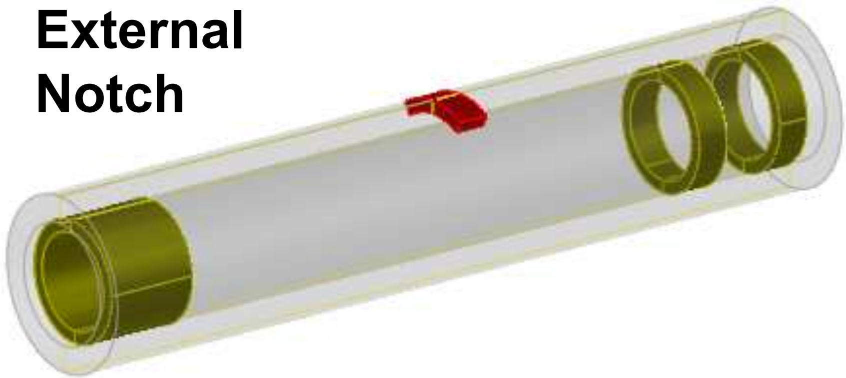


Reference:

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

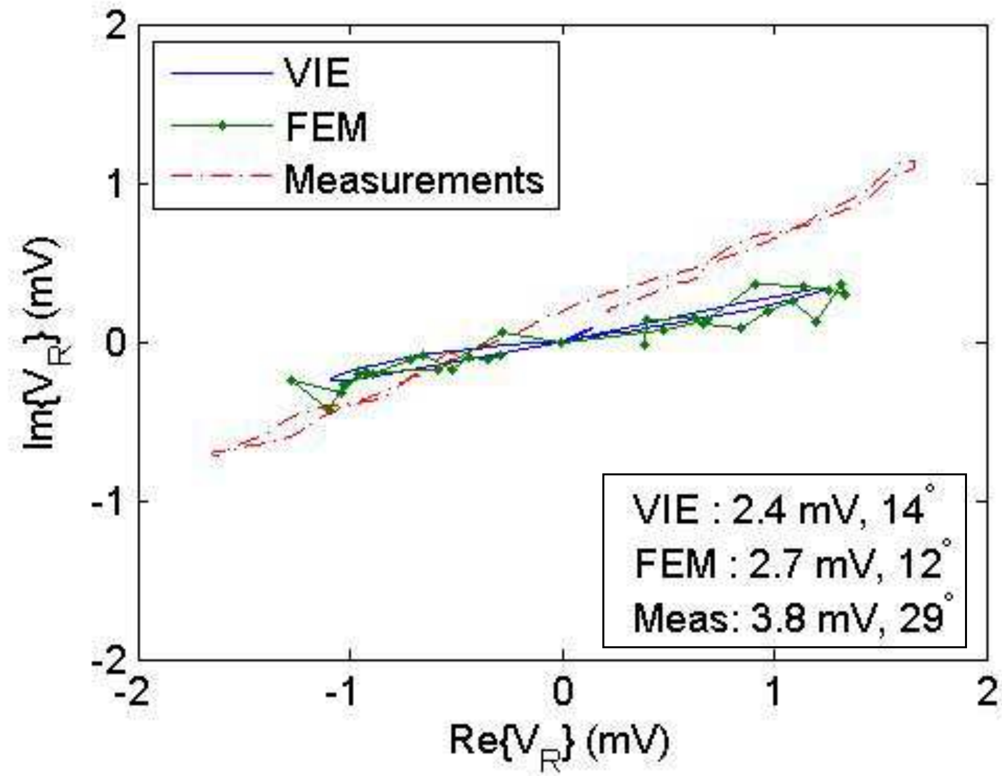
External Notch



- Flaw Parameters

50% (tube thickness)

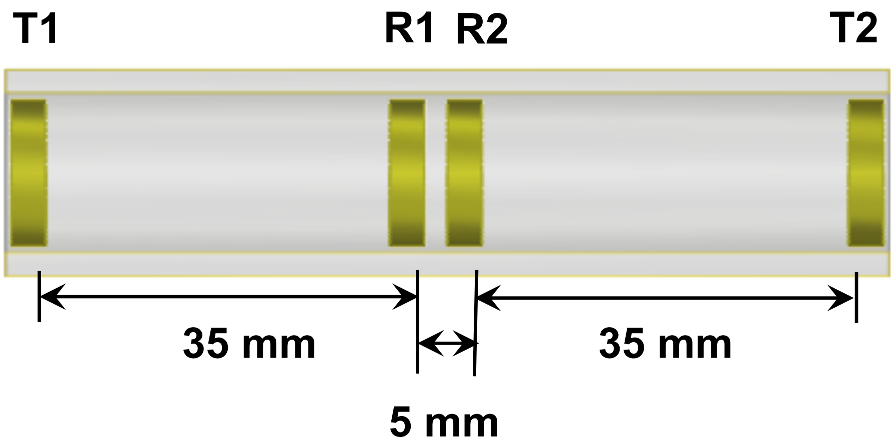
$h_f = 5\text{ mm},\ \theta = 60°$

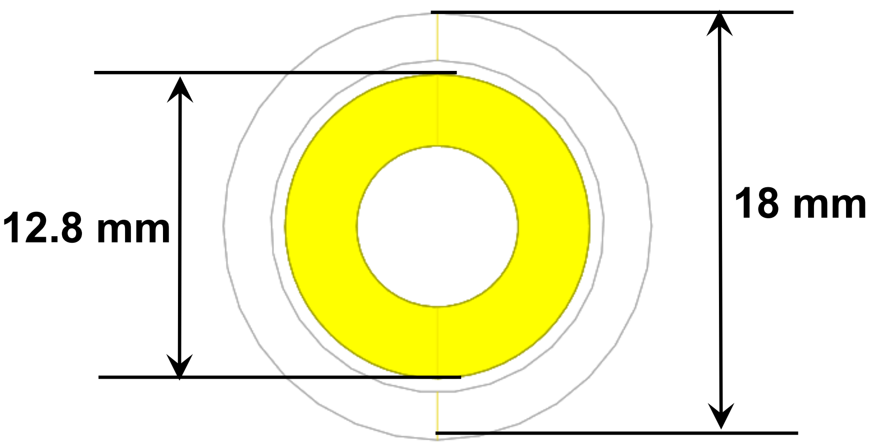


- Good agreement between VIE and FEM results
- Discrepancies with experimental data

Validation: Remote Field Probe

- Probe Layout (RFEC Probe)





- Probe Parameters

$\rho_{c_{in}} = 3.4$ mm, $\rho_{c_{out}} = 6.4$ mm
$h = 3$ mm
$N_{T_x} = 150,\ N_{R_x} = 1531$ (turns)

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

Connection:
Driving Coils: In Phase
Receivers: Differential

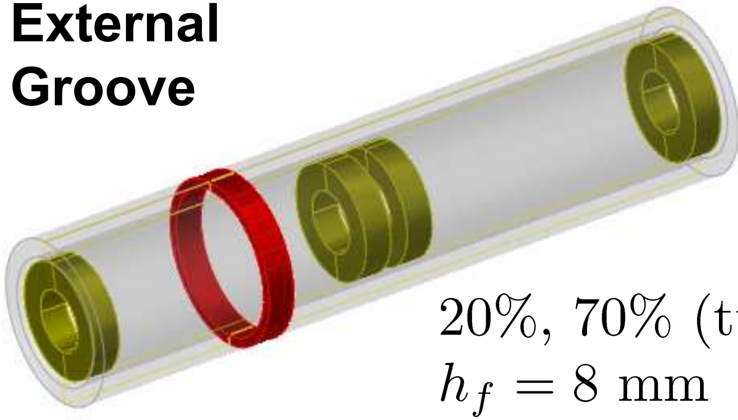
- Tube Parameters

$\rho_{in} = 7$ mm, $\rho_{out} = 9$ mm
$\sigma_t = 6.25$ MS/m, $\mu_{t_r} = 210$

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

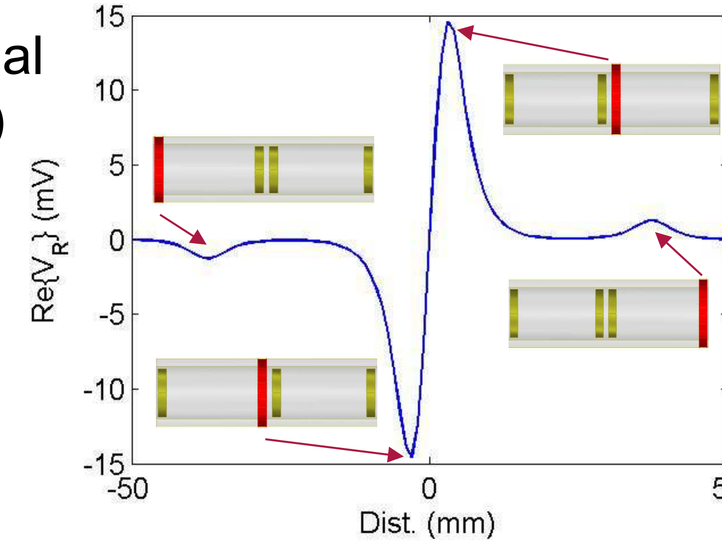
Validation: 2D Flaw

External Groove

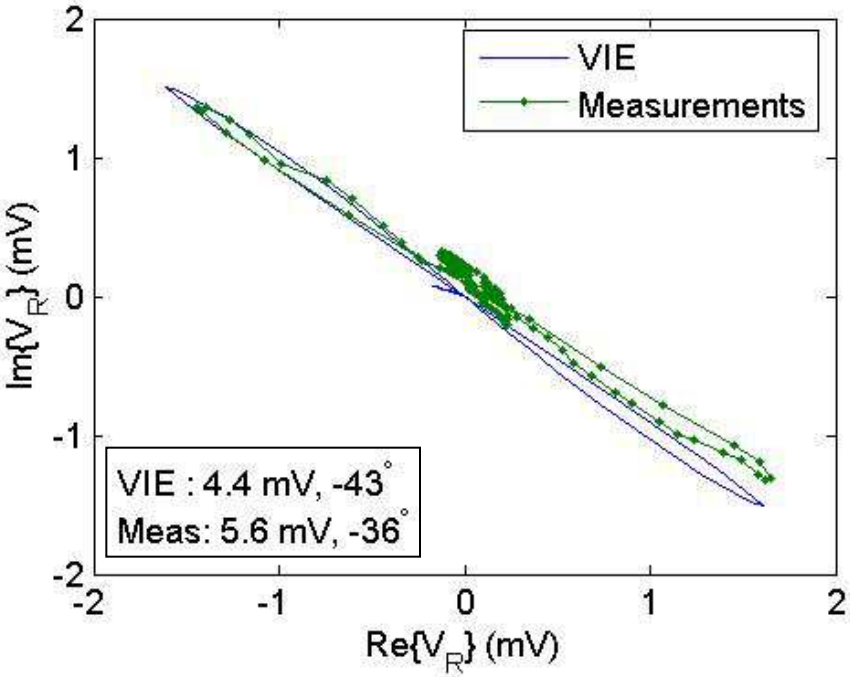


20%, 70% (tube thickness)
$h_f = 8$ mm

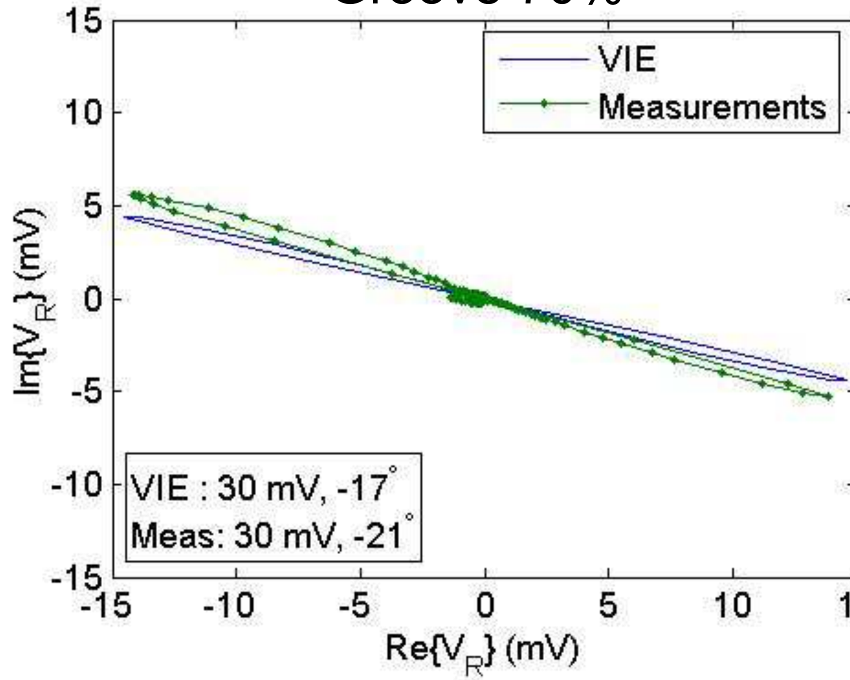
Probe Signal (Simulation)



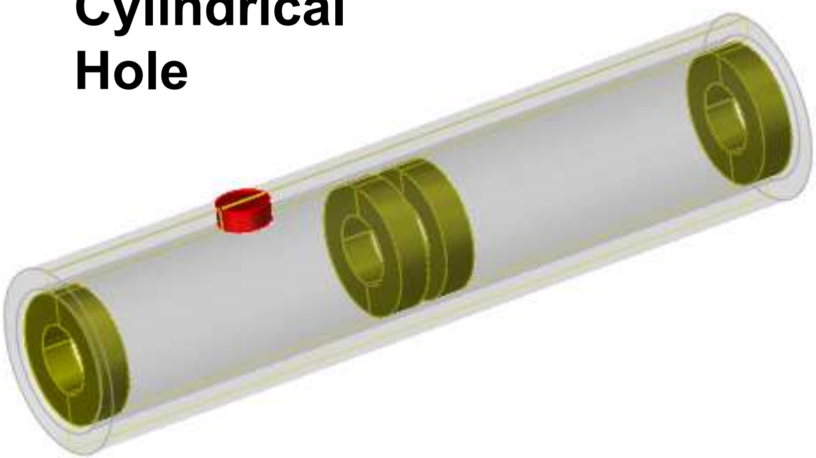
Groove 20%

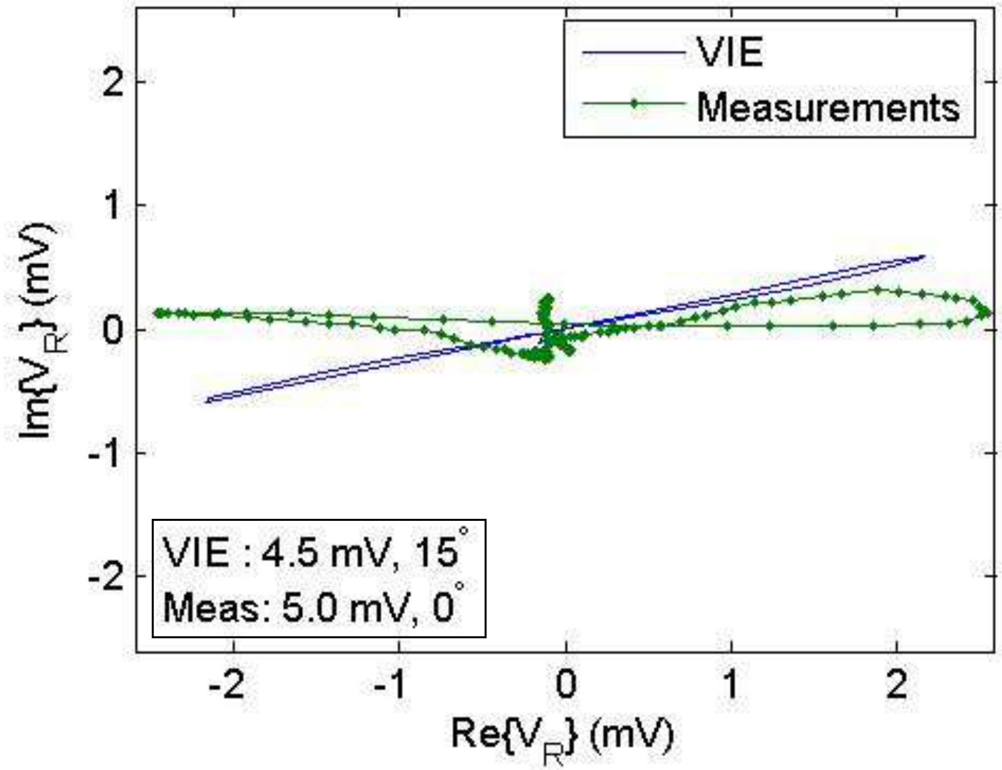


Groove 70%



Validation:3D Flaw





- Hole Dimensions
  $100\%,\ D = 5\ \mathrm{mm}$

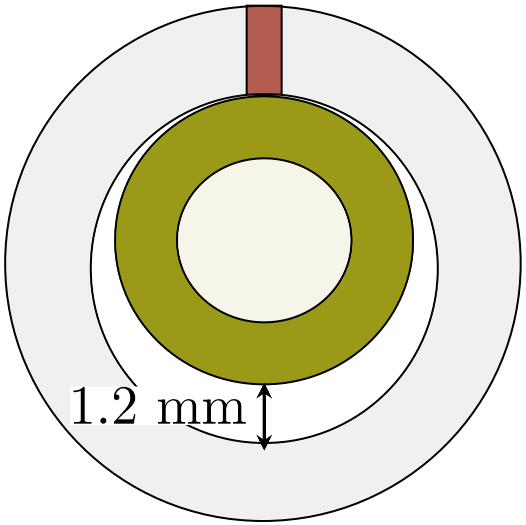
- Fabrication Effects

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

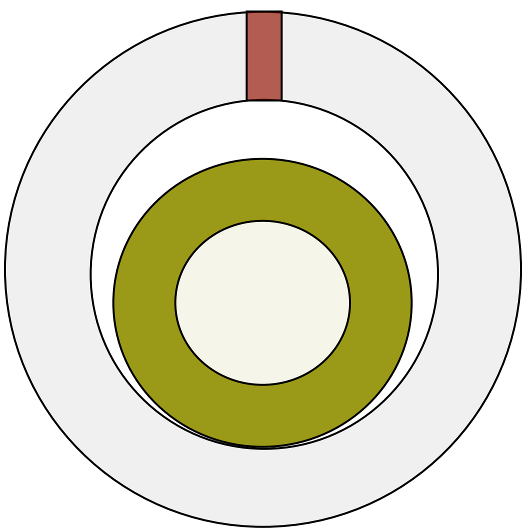
- Same behavior with the previous 3D case
- Probably due to flaw fabrication side effects

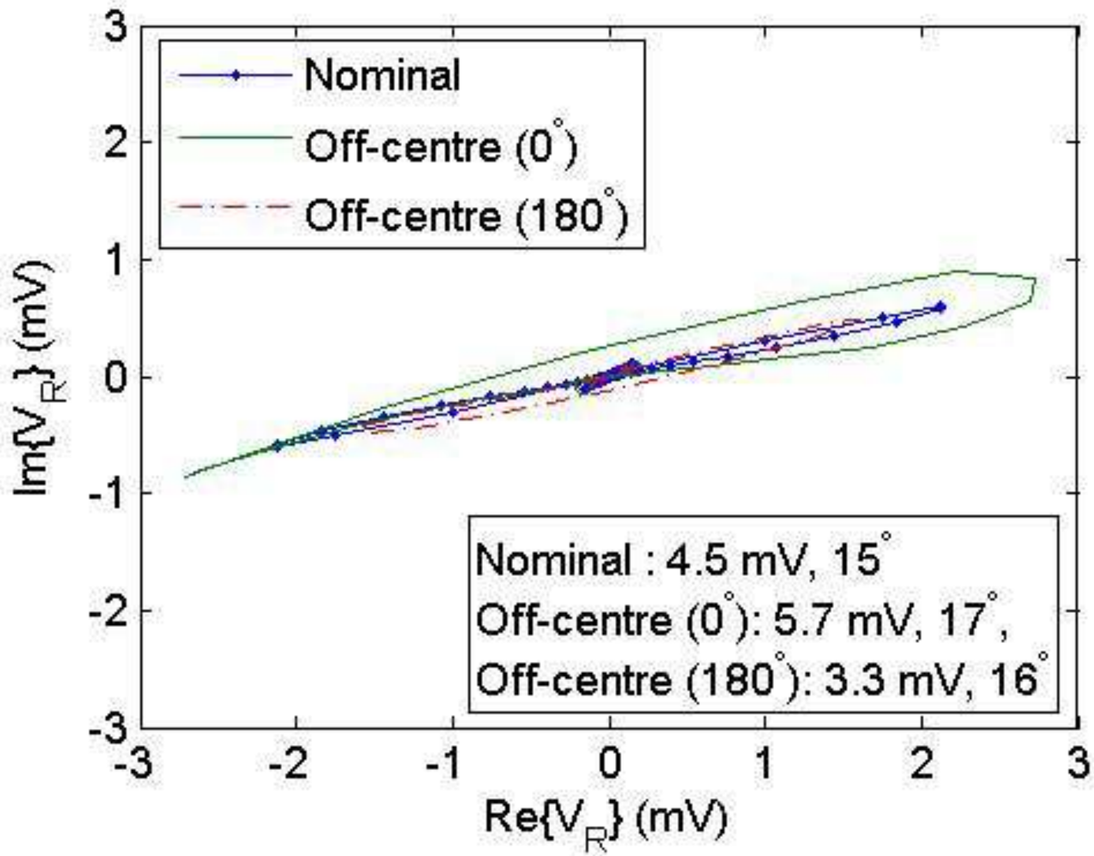
Off-centering Effect in Case of a Hole

Off-centre (0°)

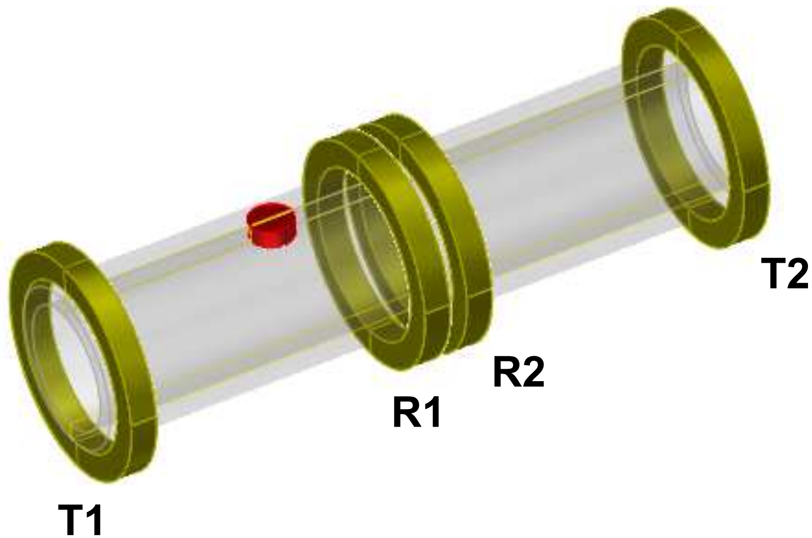


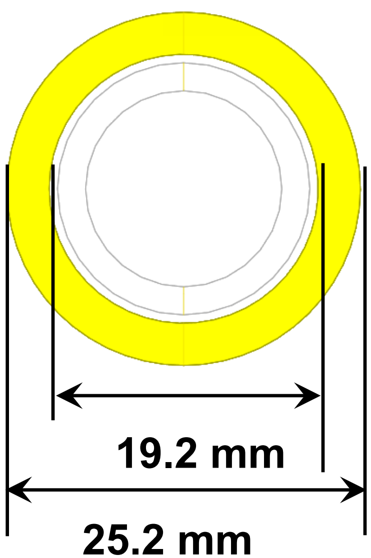
Off-centre (180°)

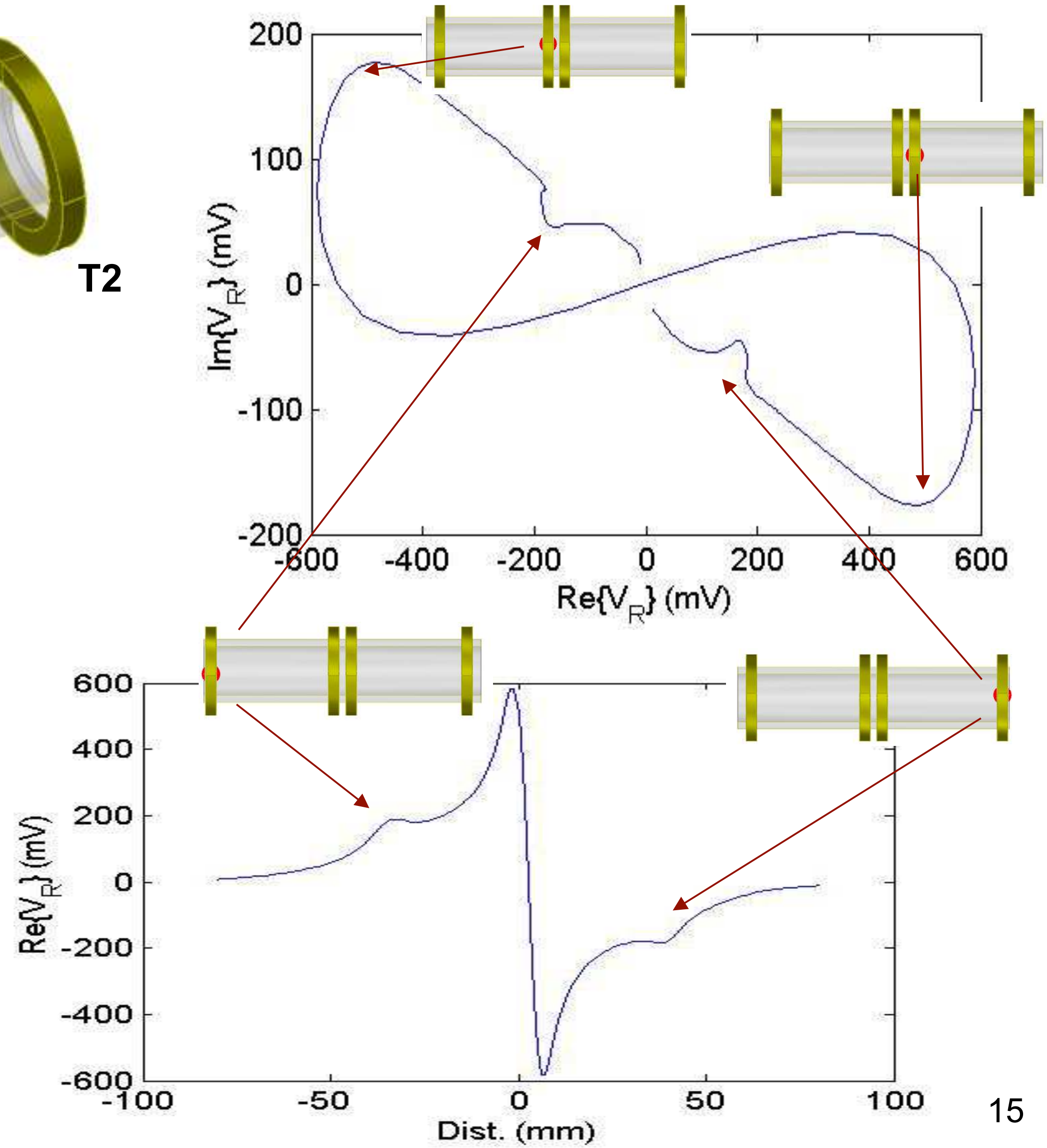




Inspection with External Probe







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