Active B_1 Imaging Using Polar Decomposition RF-CDI

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Outline

- Background
- Methodology
  - Magnetic field measurement
  - Current density field calculation
- Experimental Validations
  - Active B_1 measurement and comparison with double-angle B_1 mapping
  - Phantom experiments with disturbance pulses
  - Phantom experiment with injected currents
- Conclusions and Discussions

Background: Current Density Imaging

- Current Density Imaging (CDI) is a technique that non-invasively measures current densities in a volume using Magnetic Resonance Imaging (MRI).

- Current is applied externally.

- Low Frequency Source (5 - 100 Hz) - LFCDI
- Radio Frequency Source (64 MHz) - RFCDI

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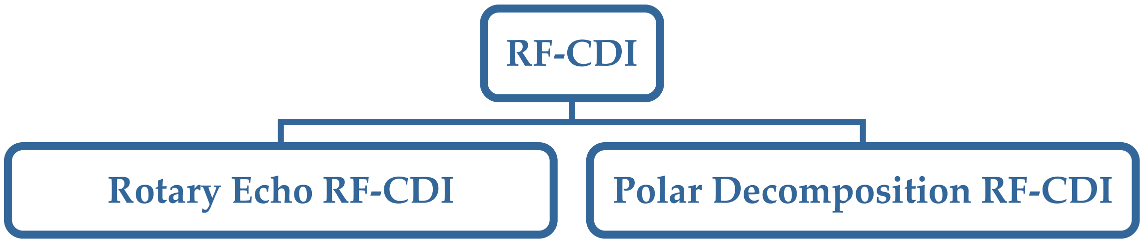
Background: Polar Decomposition RF-CDI

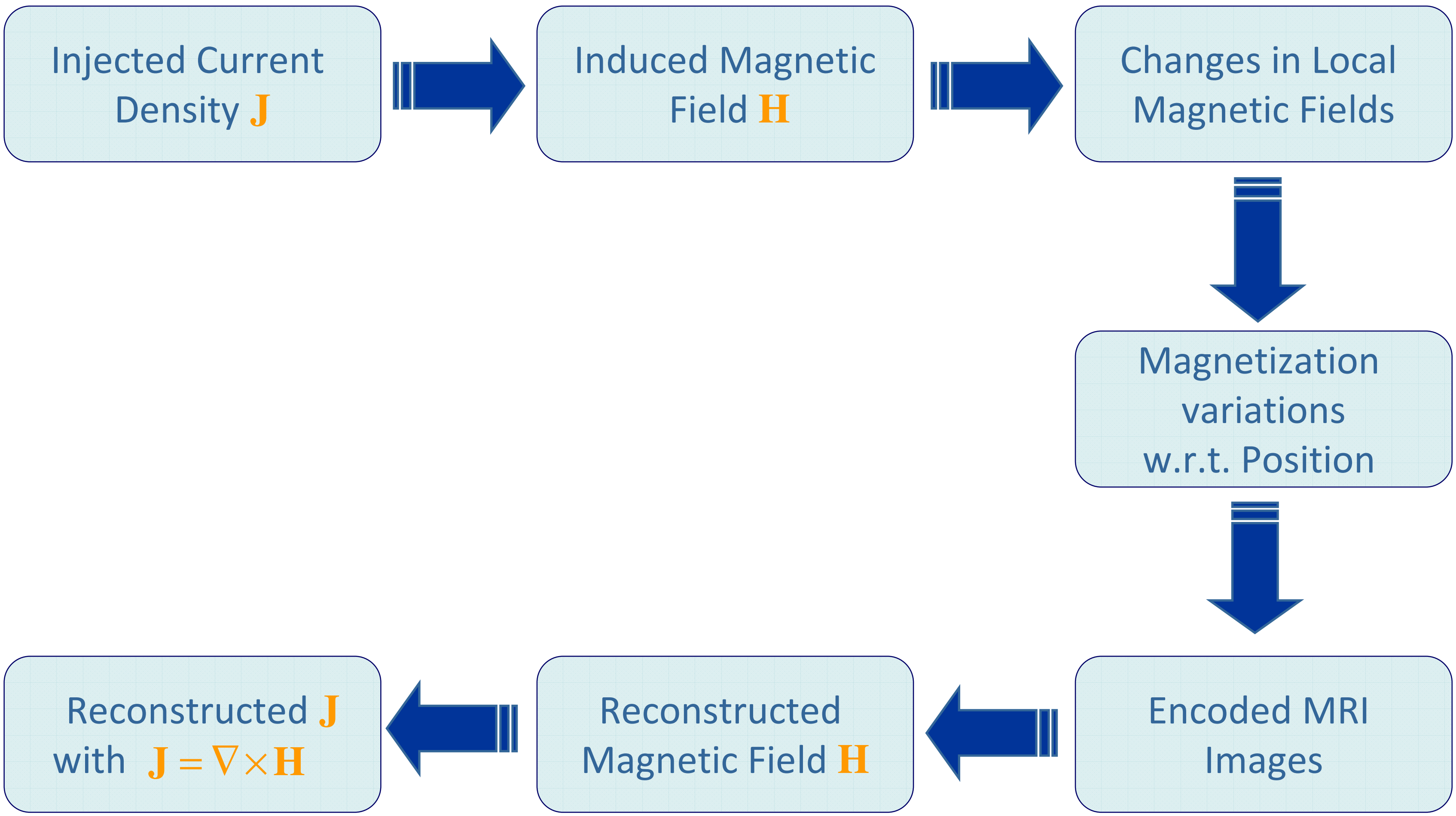
- RF-CDI Methods:



- Limitations of Rotary Echo RF-CDI
  - Magnitude of the injected current is restricted;
  - Inevitable systematic artifacts and high SAR.

- Limitations of previous Polar Decomposition RF-CDI
  - Low SNR due to phase-wrapping and axis flips.

Flowchart: How PD-RFCDI works …

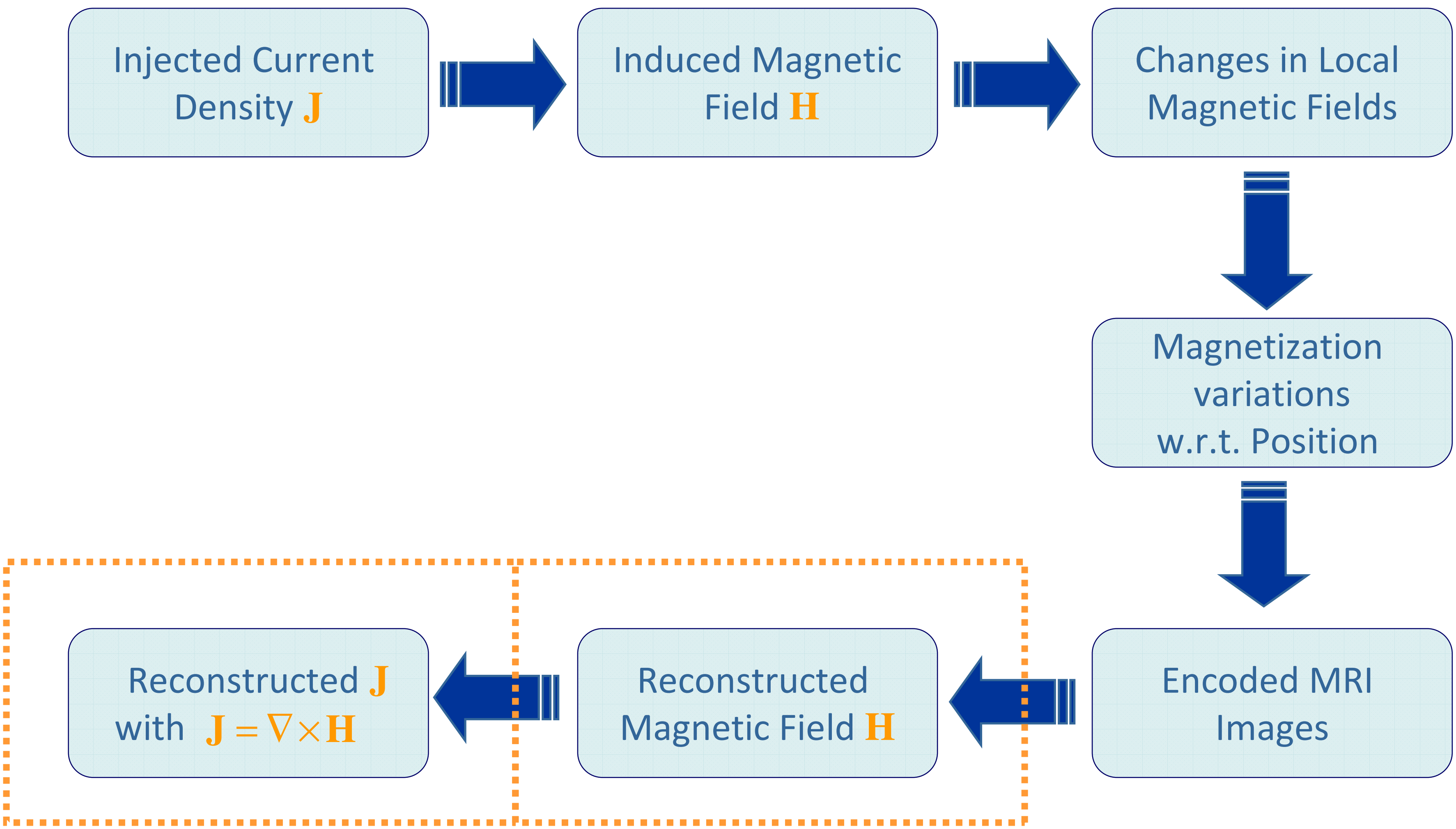


Polar Decomposition RF-CDI: Methodology

PD-RFCDI consists of two important reconstruction steps:

- Part 1: to measure the magnetic field from the rotation of magnetization measured by MRI;
- Part 2: to compute current density field from the measured magnetic field.

Flowchart: How PD-RFCDI works …



Polar Decomposition RF-CDI: Methodology (part 1)

How to measure the magnetic field from the rotation of magnetization ?

- Bloch's Equation:

$$\frac{\partial \mathbf{M}}{\partial t} = \gamma \mathbf{M} \times (\mu_0 \mathbf{H}_L) - \frac{M_z - M_z^0}{T_1} z - \frac{M_x x}{T_2} - \frac{M_y y}{T_2}$$

Current-induced Magnetic Field Component

- Physical Interpretation: Magnetization **M** rotating about the rotation axis:
  - Magnitude of **H** determines the rotation angle;
  - Orientation of **H** determines the rotation axis.

Polar Decomposition RF-CDI: Methodology (part 1)

How to measure the magnetic field from the rotation of **M**?

- Answer: to measure the rotation angle and axis of **M**.

How to measure the rotation angle and axis of **M**?

- Answer: three steps

  1. Polar Decomposition;
  2. Quaternion operation;
  3. Dual-unwrapping.

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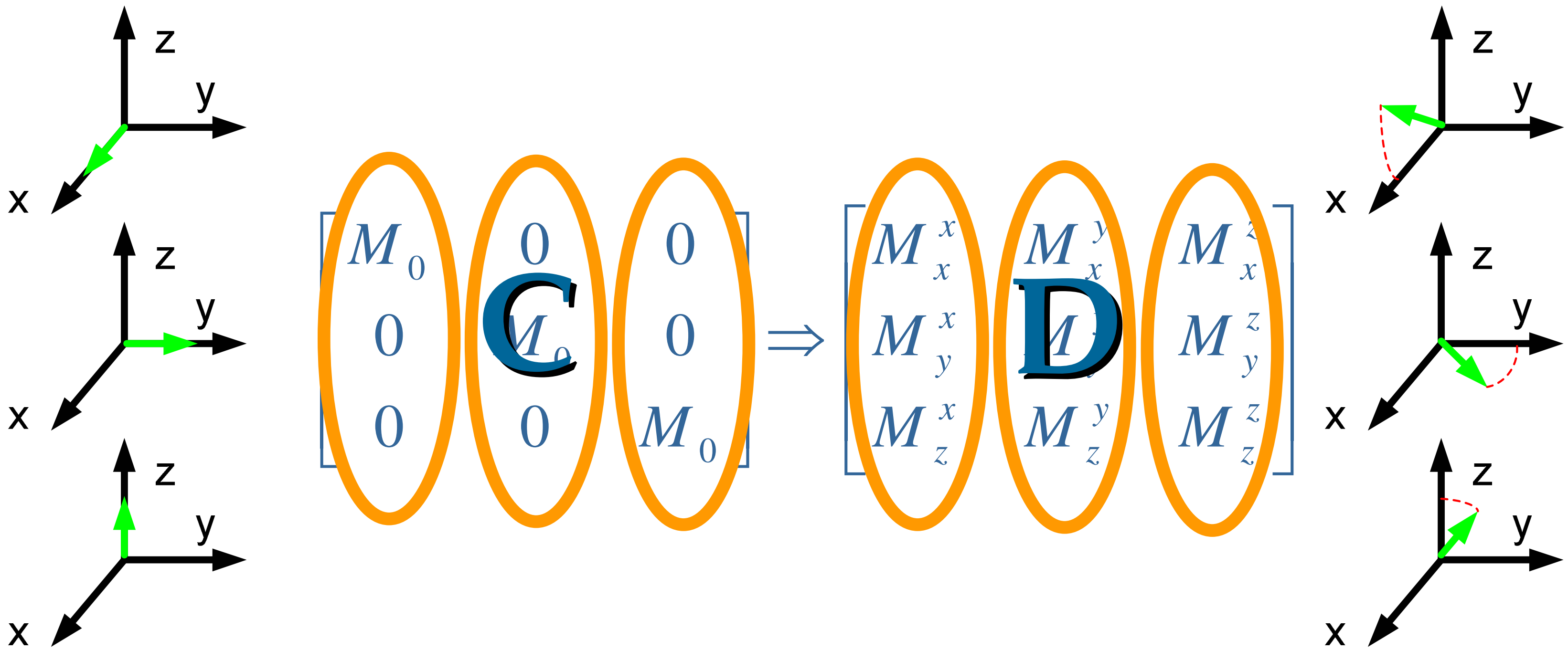
Polar Decomposition RF-CDI: Methodology (part 1)

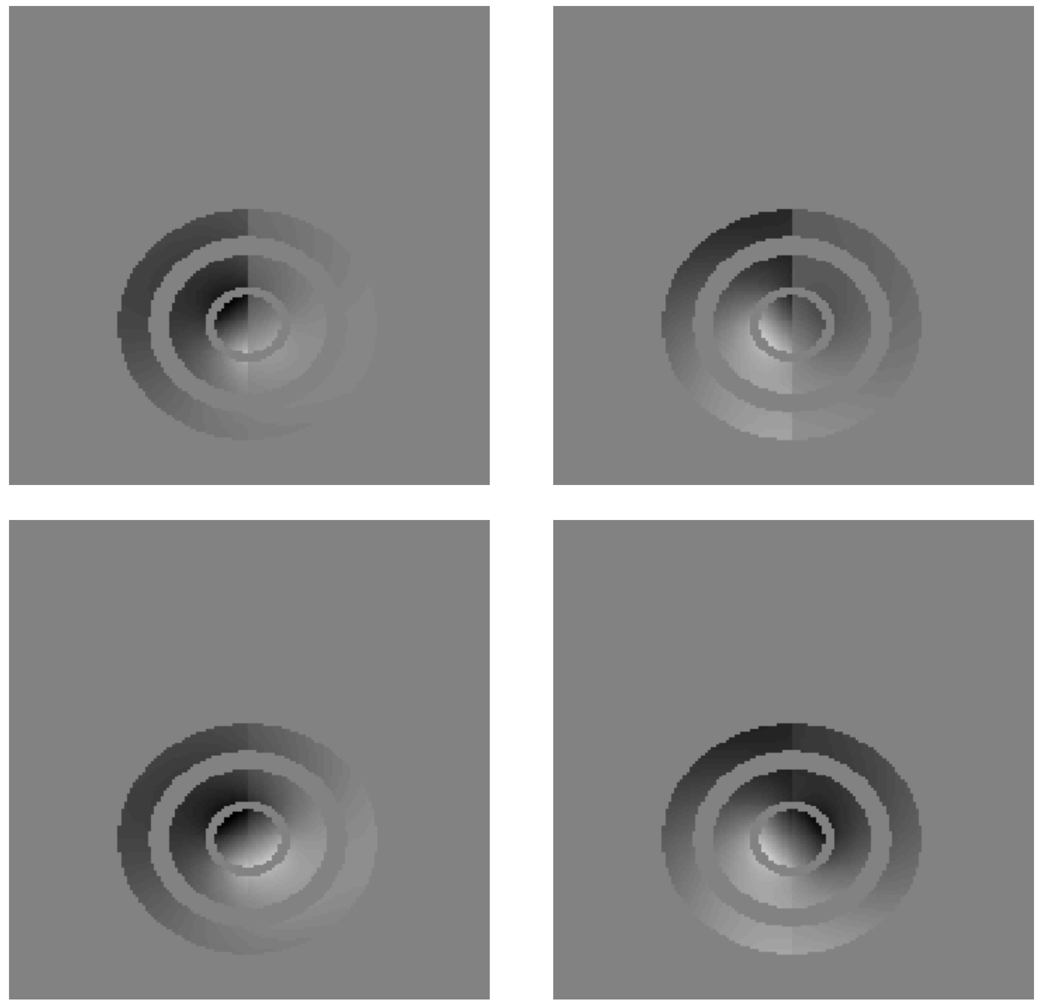
- Polar Decomposition: to extract rotation matrix from snapshots of the starting and ending positions of **M**.



$$\begin{bmatrix} M_0 & 0 & 0 \\ 0 & M_0 & 0 \\ 0 & 0 & M_0 \end{bmatrix} \Rightarrow \begin{bmatrix} M_x^x & M_x^y & M_x^z \\ M_y^x & M_y^y & M_y^z \\ M_z^x & M_z^y & M_z^z \end{bmatrix}$$

Polar Decomposition: Rotation and Relaxation Decoupling

- Top: The x and y components of **M** from the Maxwell-Bloch simulation.
- Bottom: The x and y components of **M** after polar decomposition.
- 90% decrease in the discontinuity between the left and right halves after the polar decomposition.



Polar Decomposition RF-CDI: Methodology (part 1)

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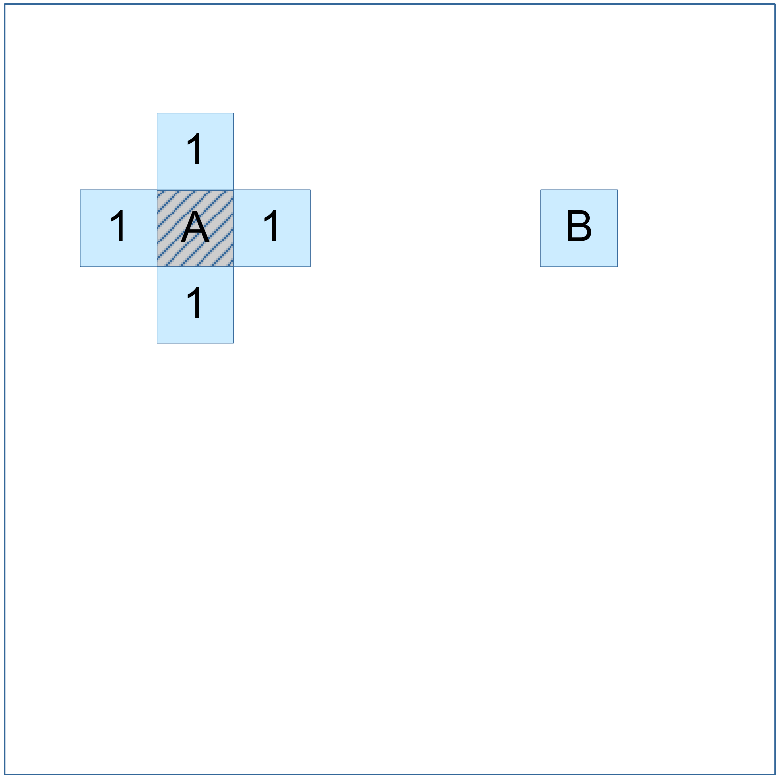
Polar Decomposition RF-CDI: Methodology (part 1)

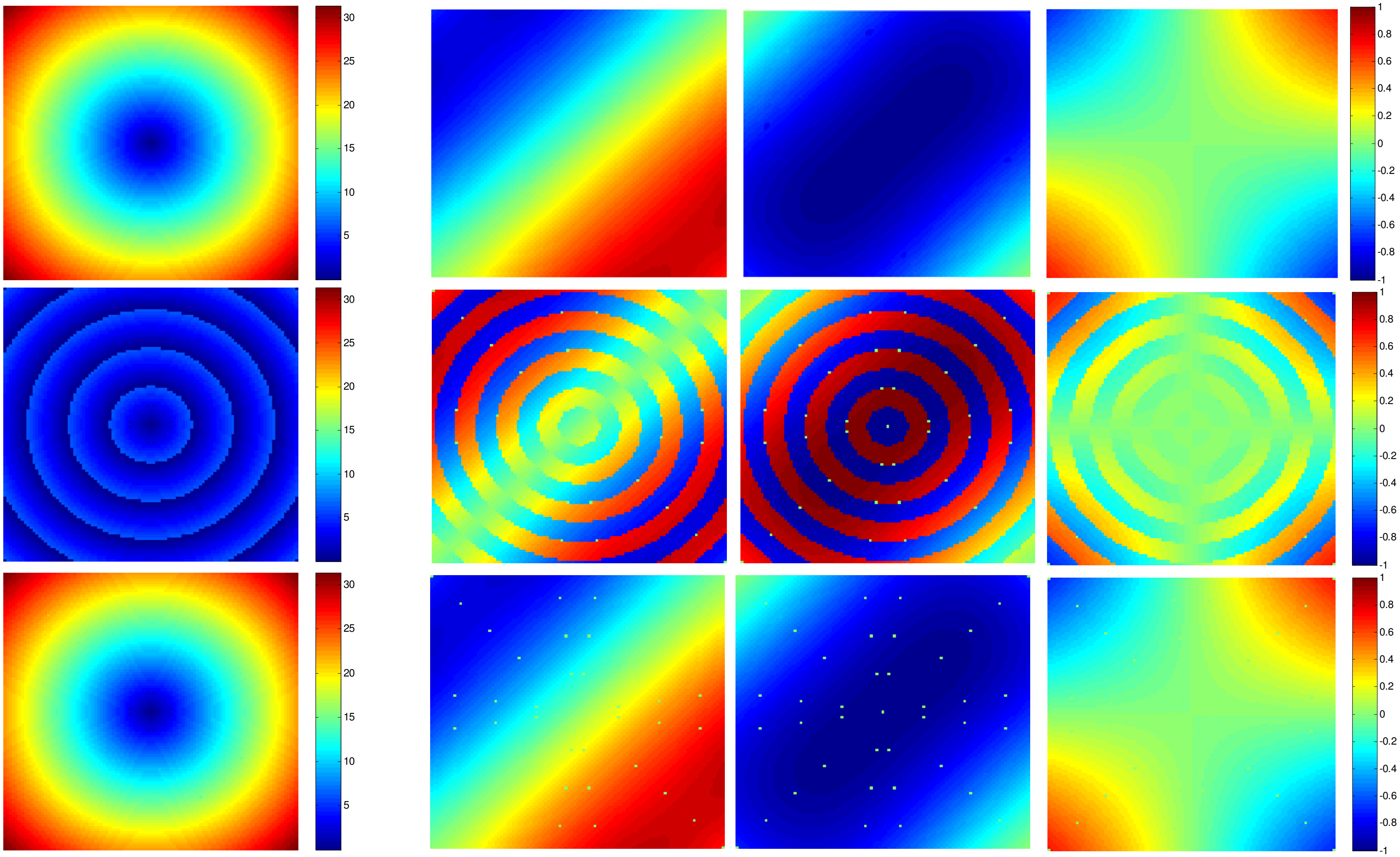
- Quaternion operation:
  - Extracts rotation angle and rotation axis information from the rotation matrix.
  - Introduces phase wraps and axis false-flips in regions where rotation angles reach multiples of π.
- Dual-unwrapping:
  - Unwraps the rotation angle and rotation axis that have been falsely interpreted in quaternion conversion.

Dual-unwrapping: Flood-fill algorithm

- Start from initial seed point A
- remove false flips and phase wraps in the neighborhood
- Find the next pixel with the highest quality value
- Set it to be the next seed point
- Probe the neighbourhood of the new seed point, remove false flips and phase wraps



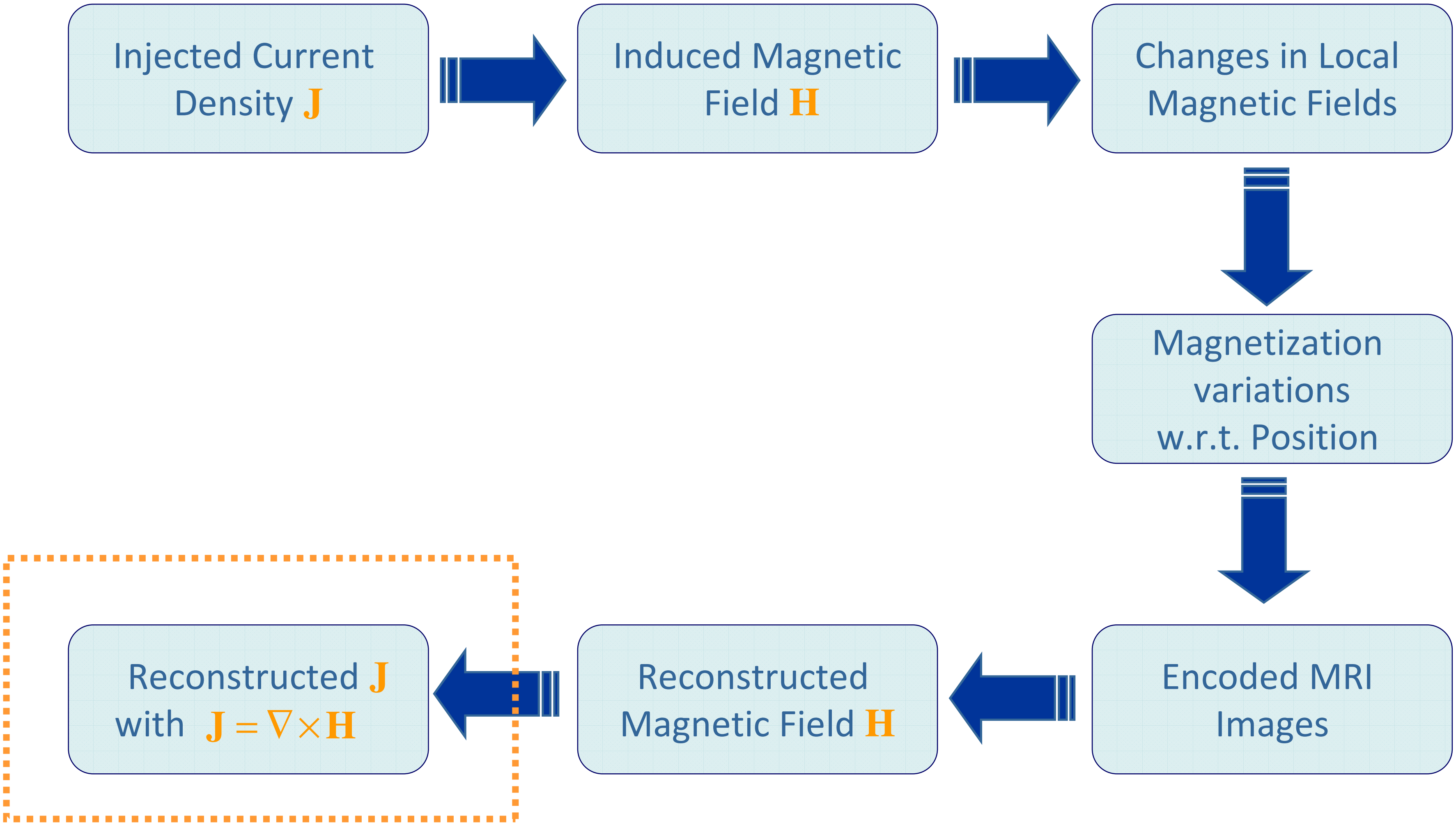
Dual-unwrapping: simulations



Rotation angle

x y z components of rotation axis

Flowchart: How PD-RFCDI works …



Polar Decomposition RF-CDI: Methodology (part 2)

How to compute current density field from the magnetic field ?

- Current Density field **J** is calculated by taking the curl of magnetic field **H**: $\mathbf{J} = \nabla \times \mathbf{H}$.
- When single orientation assumption $\partial H_z / \partial z \ll |J_z|$ is met, current densities can be computed through

$$J_z = j_z e^{j\varphi_z} = 2\left[\frac{\partial \tilde{H}_y^l}{\partial x} - \frac{\partial \tilde{H}_x^l}{\partial y}\right] + 2j\left[\frac{\partial \tilde{H}_x^l}{\partial x} + \frac{\partial \tilde{H}_y^l}{\partial y}\right]$$

- Conclusion: only the transverse magnetic field components are required to compute the longitudinal component of RF current density vectors.

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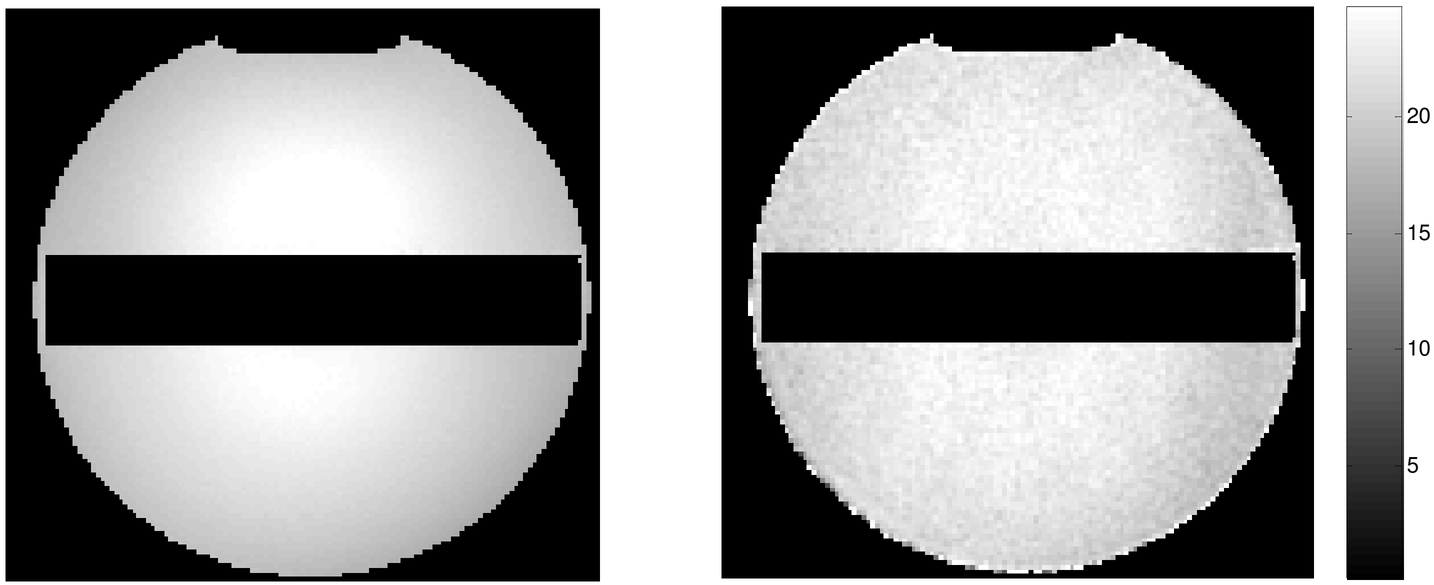
Validations: Double Angle vs. PD-RFCDI

- Double angle B_1 mapping method:
  - Conceptually simple
  - Straightforward implementation
  - One of the gold standards for active B_1 mapping

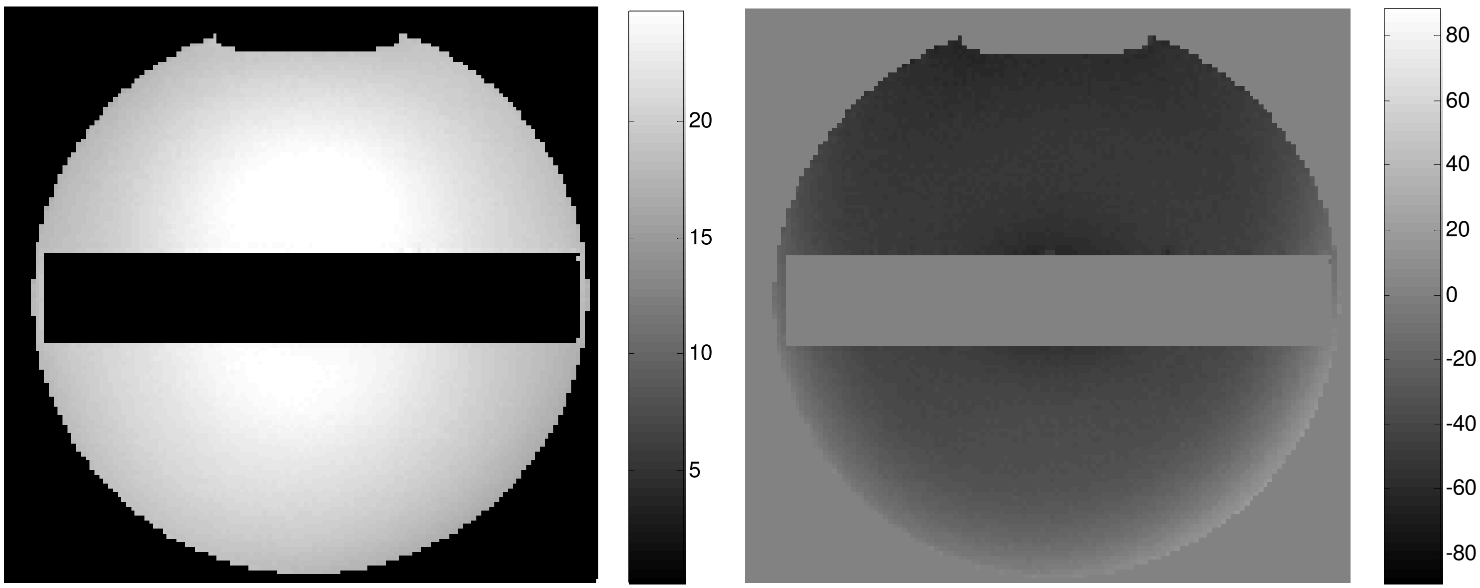
- Experiment settings:
  - A GE manufactured acrylic phantom was used.
  - GE bird cage head coil used as transmit/receive.
  - Flip angles $\alpha_1 = 20^o$ and $\alpha_2 = 40^o$
  - Excitation pulse of PD-RFCDI was calibrated to match the parameters in the double angle method.

Validations: PD-RFCDI v.s. Double Angle



Comparison of the measured flip angle using polar decomposition method (left) and the double angle mapping methods (right)

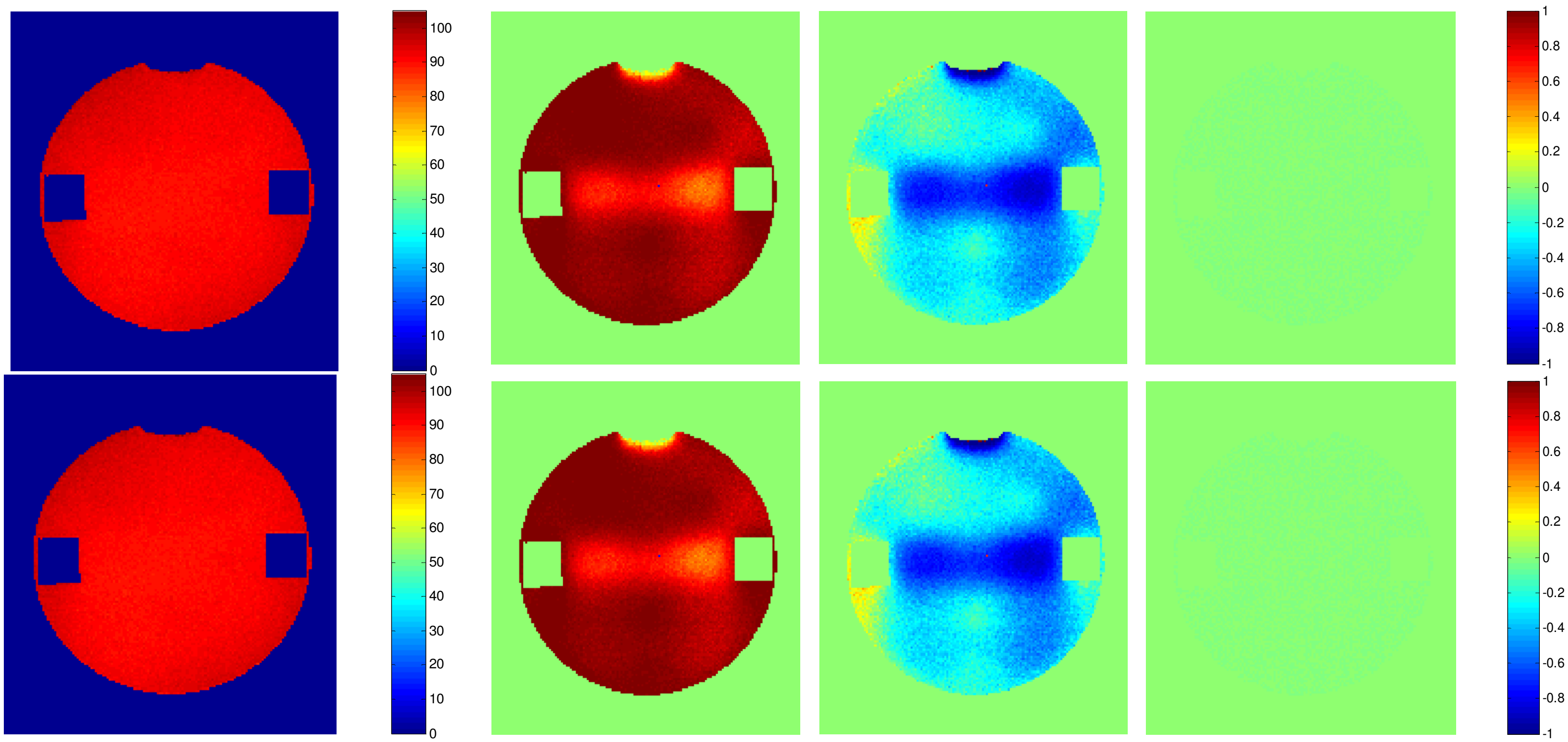
Validations: Double Angle vs. PD-RFCDI



PD-RFCDI is able to measure the phase information of the active B_1 field

Polar Decomposition RF-CDI with Disturbance Pulses

- A hard 90 pulse was applied to the RF excitation coil to create a 90-degree tip angle.
- The experiment was conducted on a GE manufactured acrylic phantom.

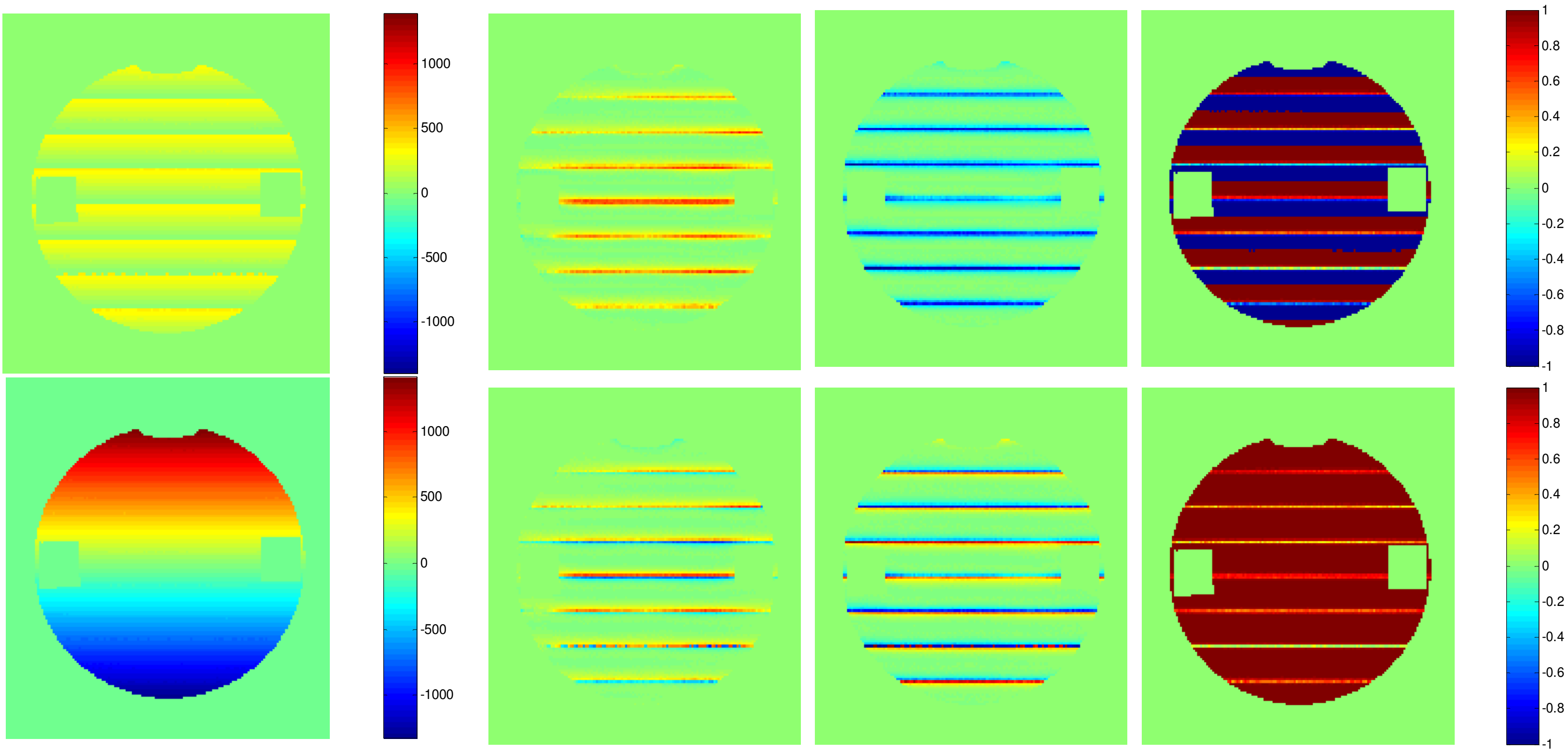


Rotation angle

x y z components of rotation axis

Polar Decomposition RF-CDI with Disturbance Pulses

- A disturbance pulse was applied to the gradient X coil to create a linearly increasing magnetic field along the x-axis.
- Pulse duration was 8.2 ms and the relative pulse amplitude was 0.02.

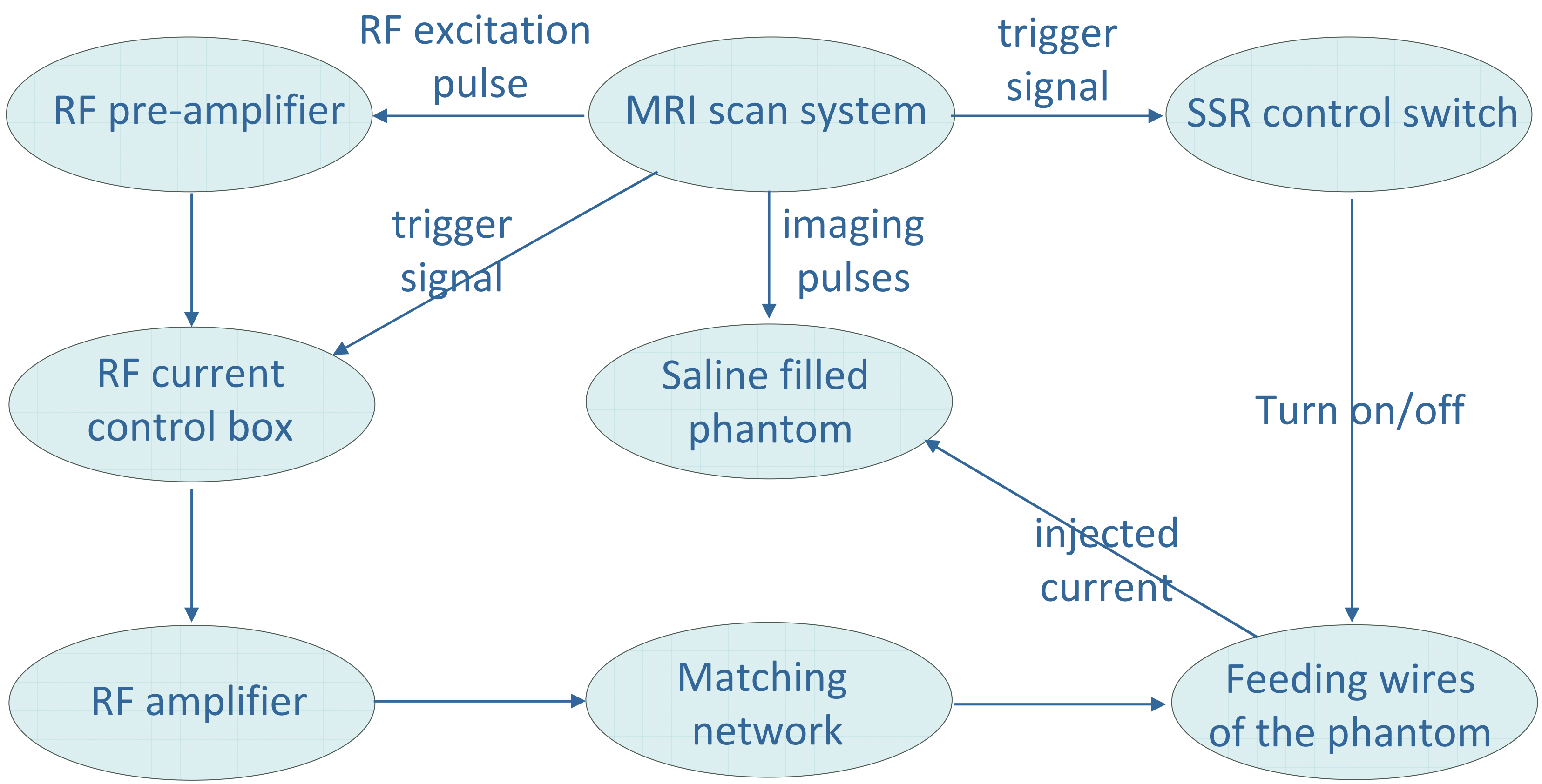


Rotation angle

x y z components of rotation axis

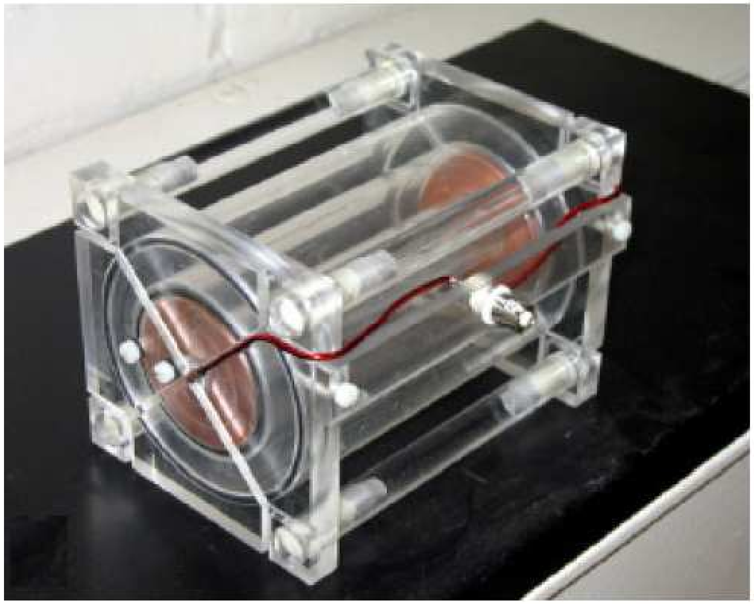
Polar Decomposition RF-CDI with Injected Current

- Experiment settings



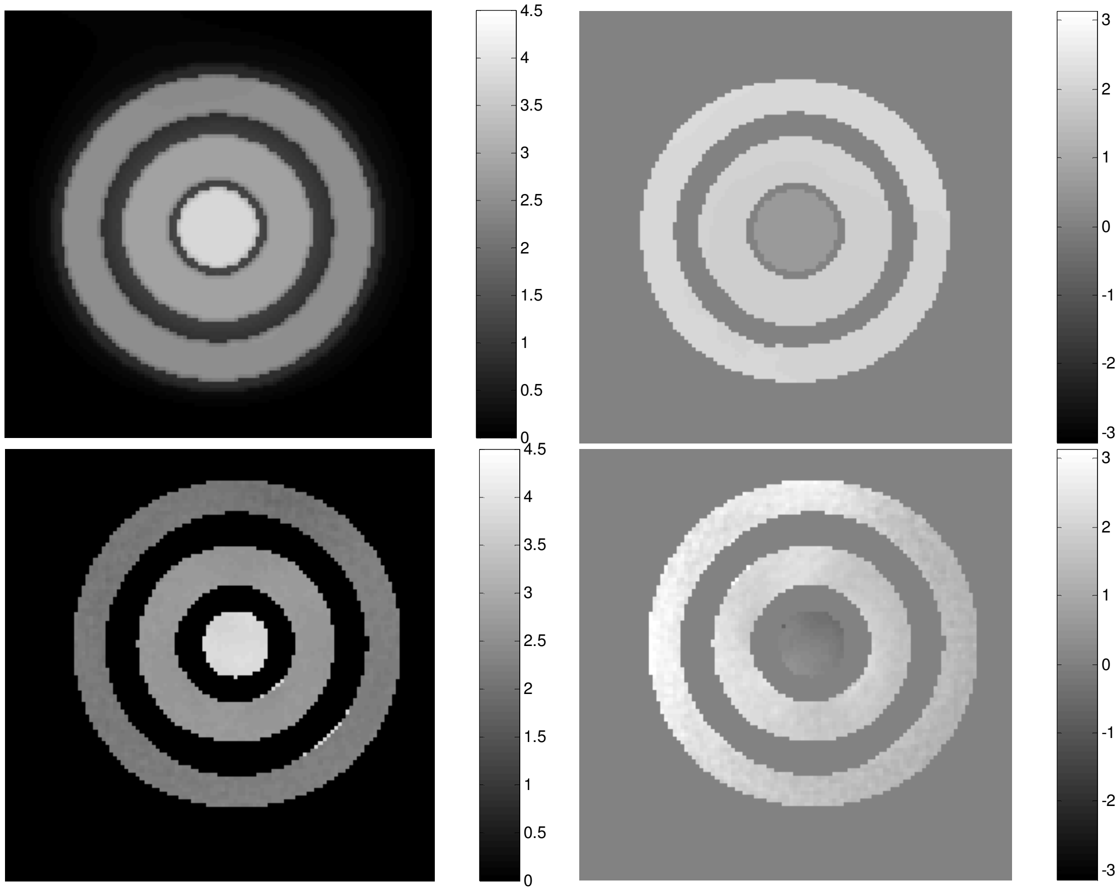
Polar Decomposition RF-CDI: Phantom Experiment

- Phantom settings
  - Three-chamber phantom;
  - Copper electrodes covering only the inner two chambers;
  - Center chamber filled with conductive saline;
  - Outer two chambers filled with $CuSO_4$ doped water.



Polar Decomposition RF-CDI with injected current

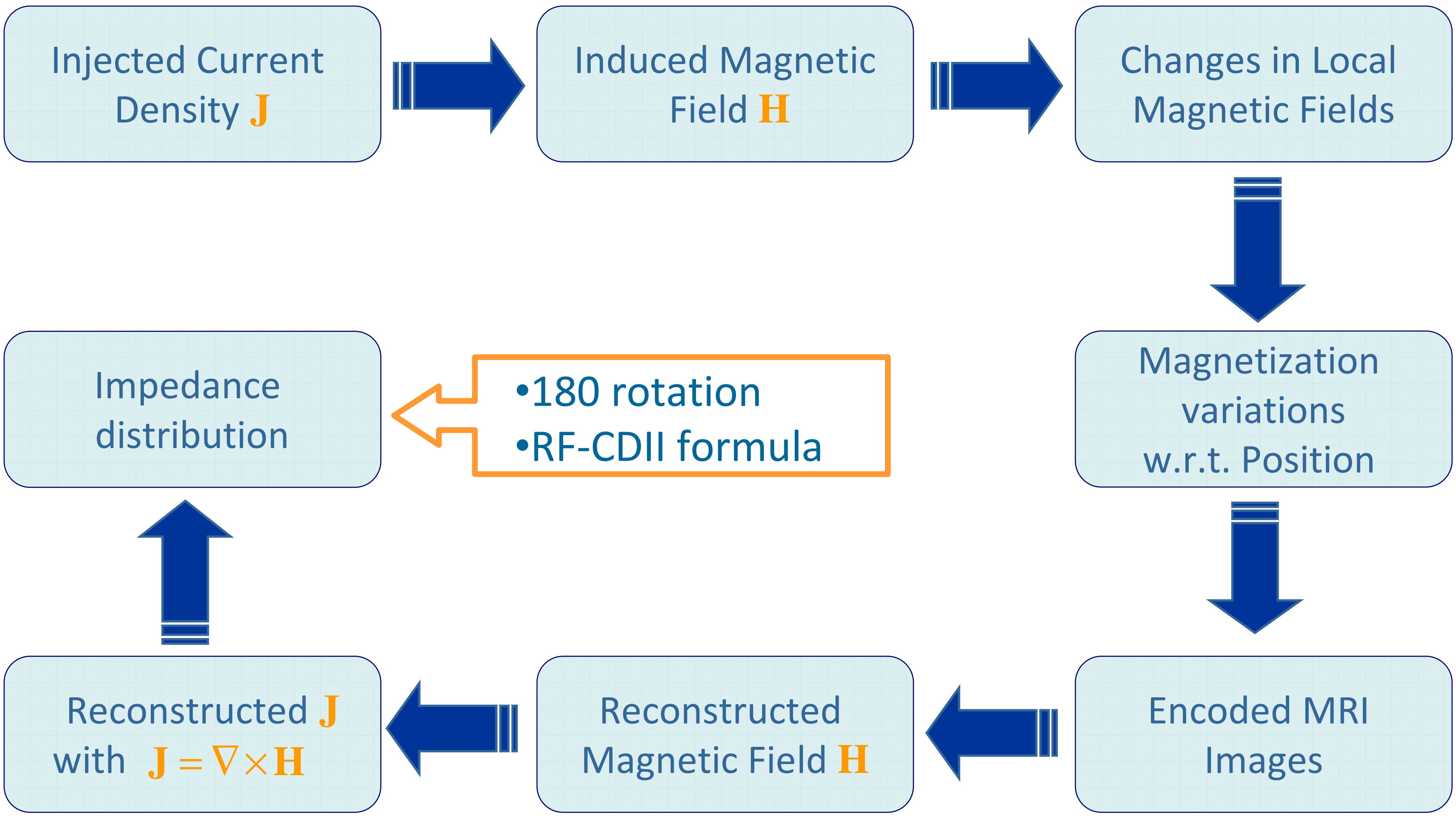
- Current magnitude and phase vary from the inner to the outer chamber;
- Consistent reconstruction results with comparison to the FDTD simulation.



Current magnitude

Current phase

Updated Flowchart: How RF-CDII works …



Conclusions and Discussions

In this work, we have:

- compared PD-RFCDI with the double angle B1 mapping method to confirm the validity of PD-RFCDI measurements.
- conducted the phantom experiments that showed PD-RFCDI is able to detect disturbances applied through RF and gradient coils;
- performed the phantom experiment with injected currents on a commercial scanner;
- proved that the new, improved PD-RFCDI is able to reconstruct currents of a much larger dynamic range.

Future work includes:

- to perform full vector PD-RFCDI experiment with 180 rotations;
- to implement RF impedance imaging algorithm (RF-CDII) with the measured RF current information.

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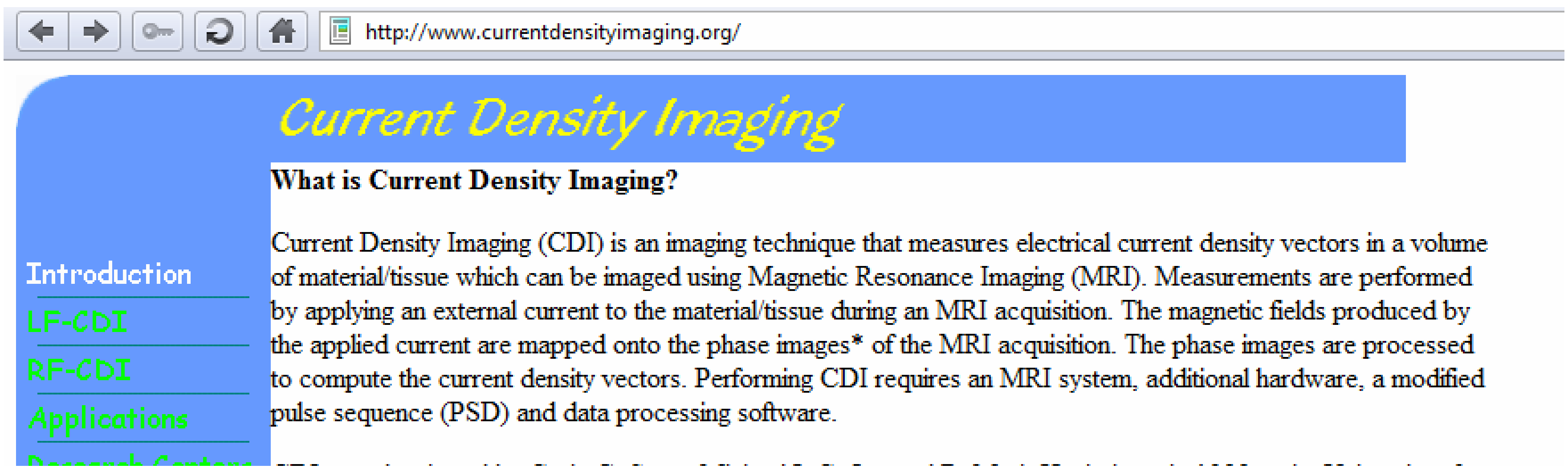
For More Information on CDI, RFCDI, PD-RFCDI…

www.currentdensityimaging.org

- Software downloads;
- Reference papers;
- Projects overviews;
- Contact information.



Thanks for your attention!