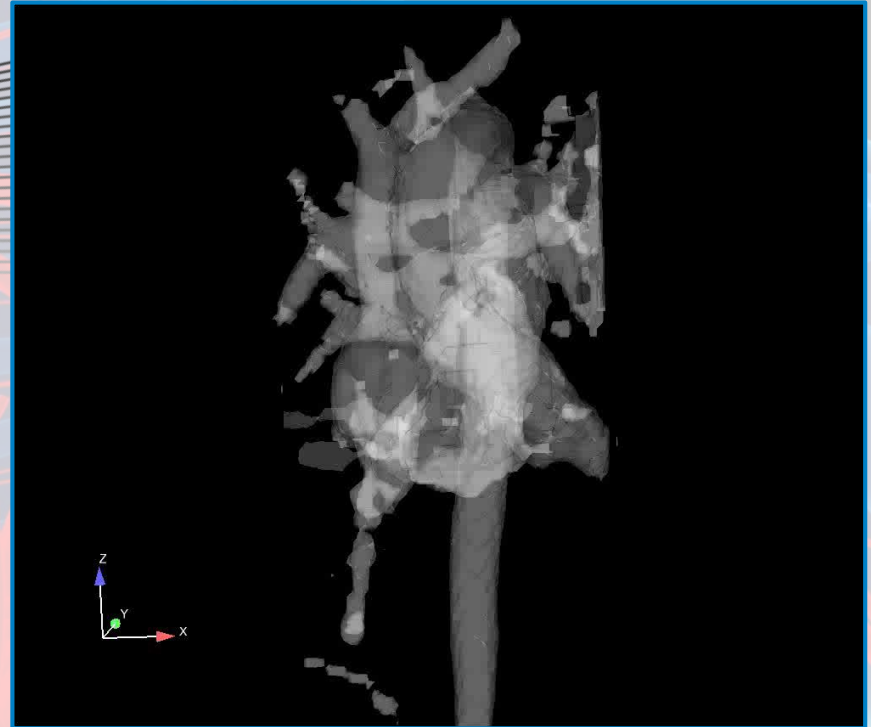
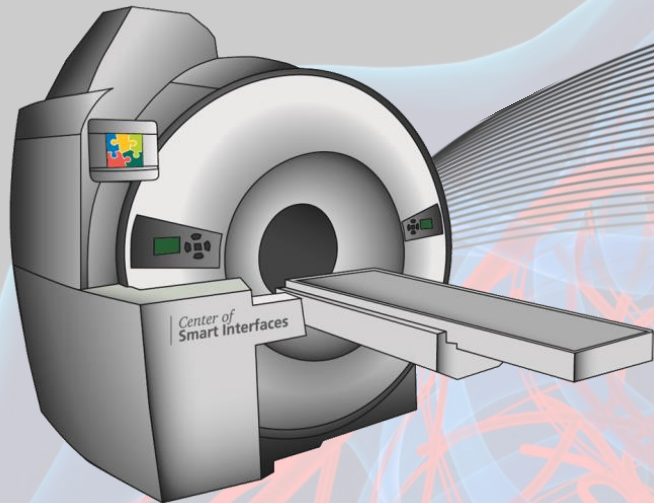


# Measurement Errors in Magnetic Resonance Imaging of Fluid Flows



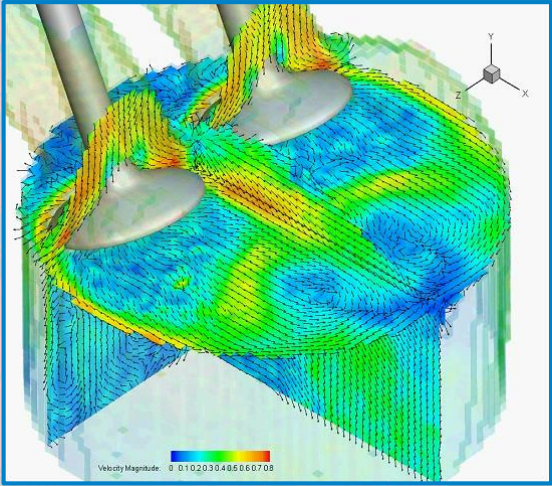
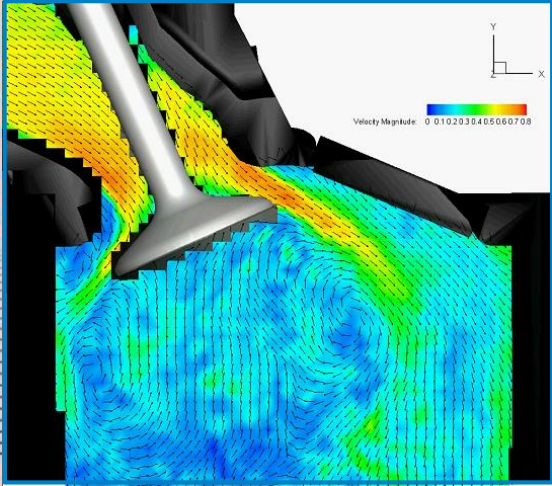
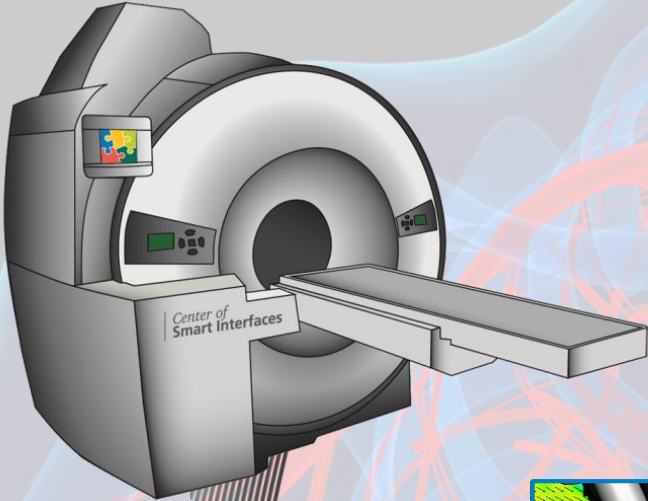
# Flow Visualization with MRI

from Medicine to Engineering

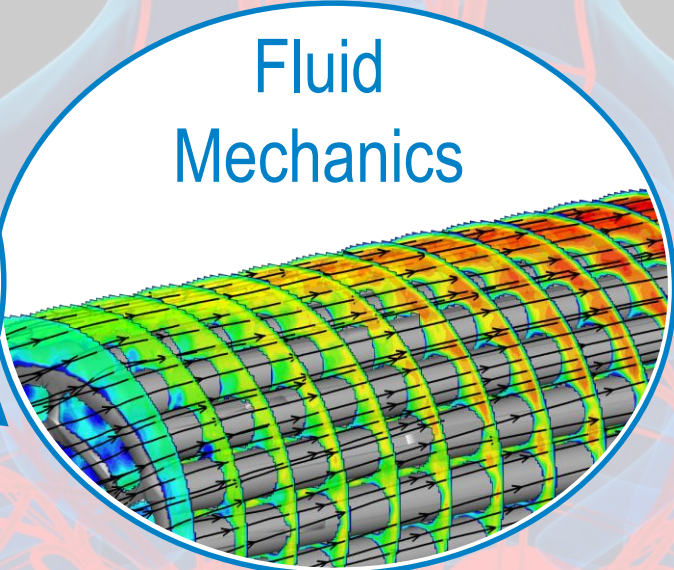


# Flow Visualization with MRI

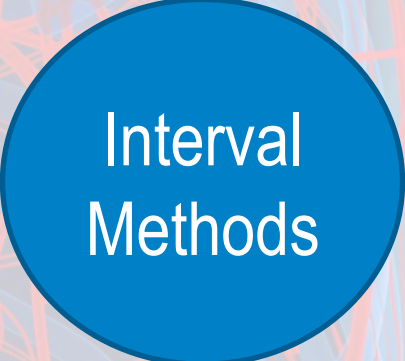
from Medicine to Engineering



# Our Niche

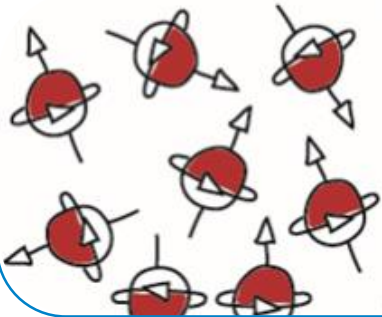


<100 researchers  
world wide

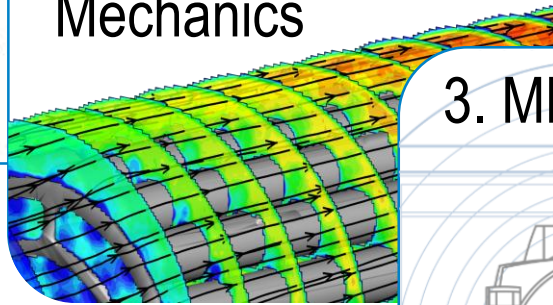


# Today's Agenda

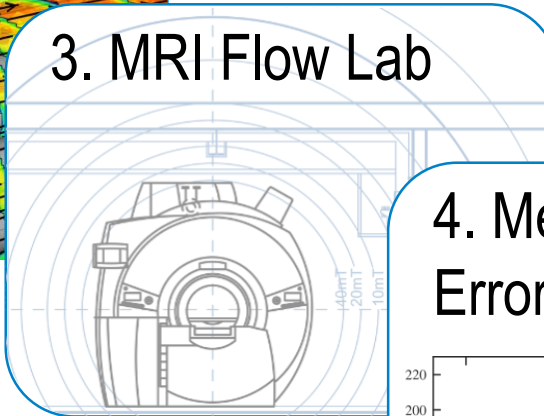
## 1. MRI principles



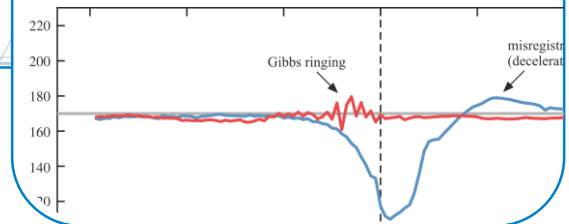
## 2. MRI in Fluid Mechanics



## 3. MRI Flow Lab

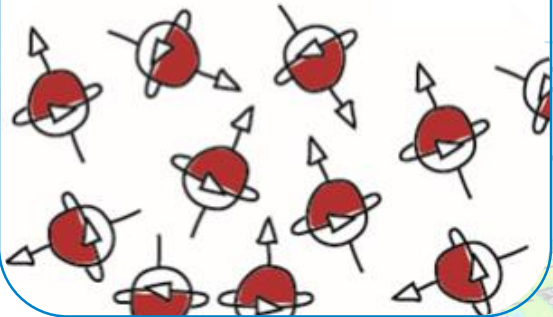


## 4. Measurement Errors in MRI



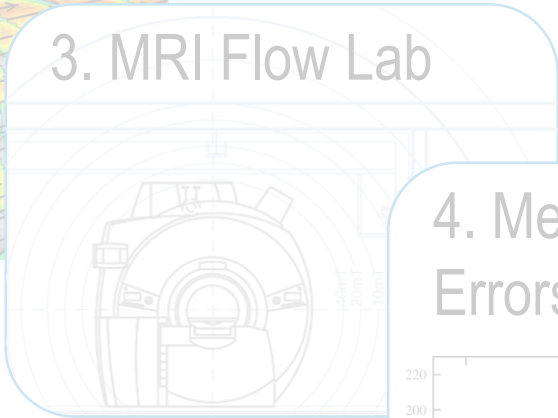
# Today's Agenda

## 1. MRI principles

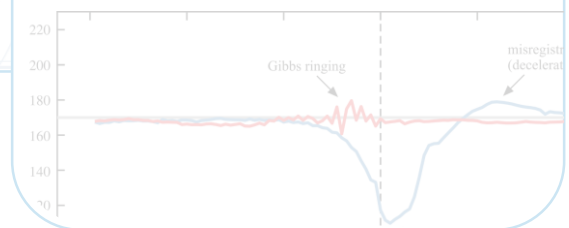


MRI in Fluid  
Mechanics

## 3. MRI Flow Lab



## 4. Measurement Errors in MRI

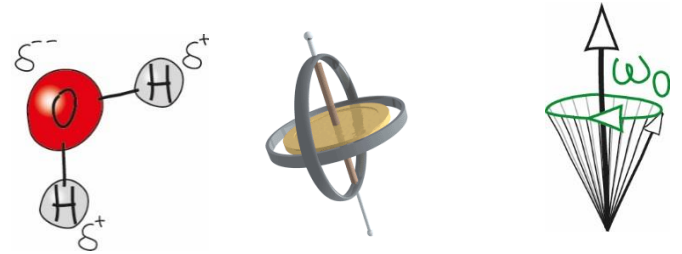


# Theoretical Background

## 1. MRI Principles

### The spin

- quantum mechanical property
- the spins align with field lines
- not stationary: precession motion
- precession frequency depends on field strength:

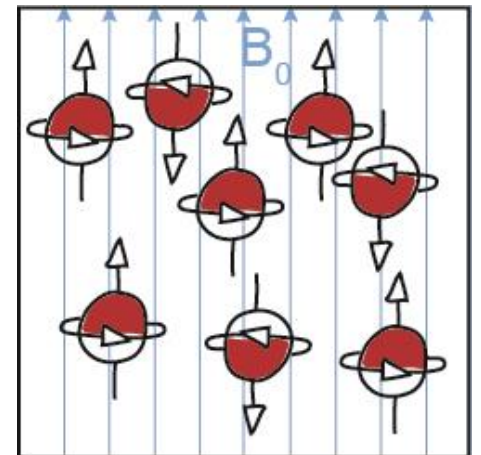


### Larmor frequency:

$$\omega = \gamma B$$

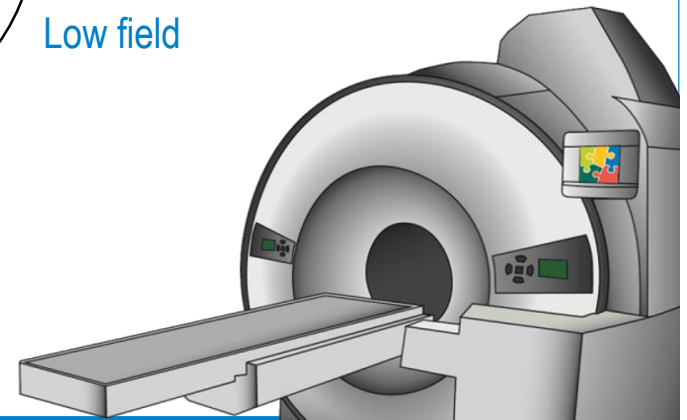
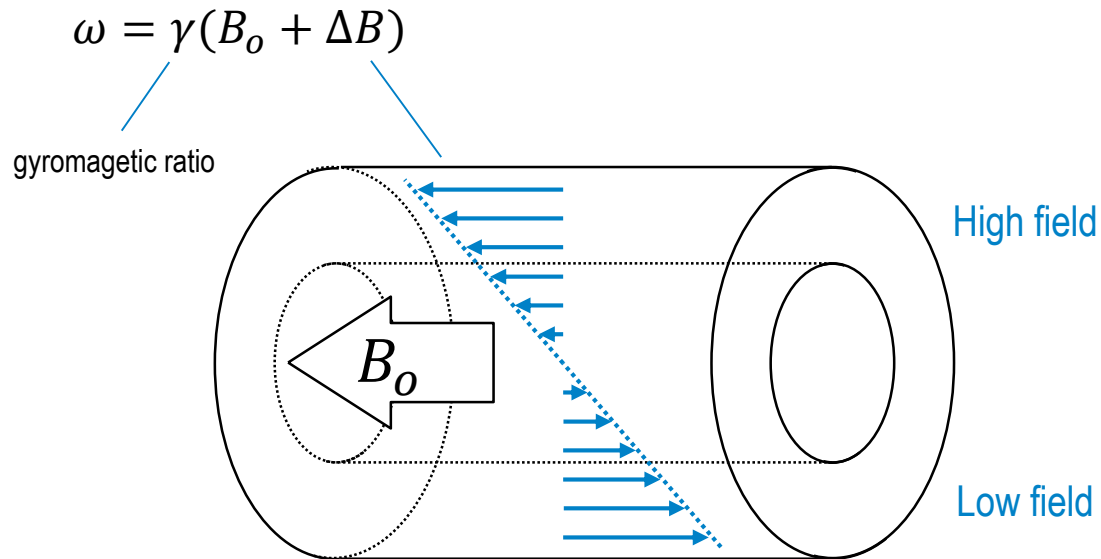
↓ local field strength

↑ gyromagnetic ratio



# Basics of MR Imaging

## 1. MRI Principles

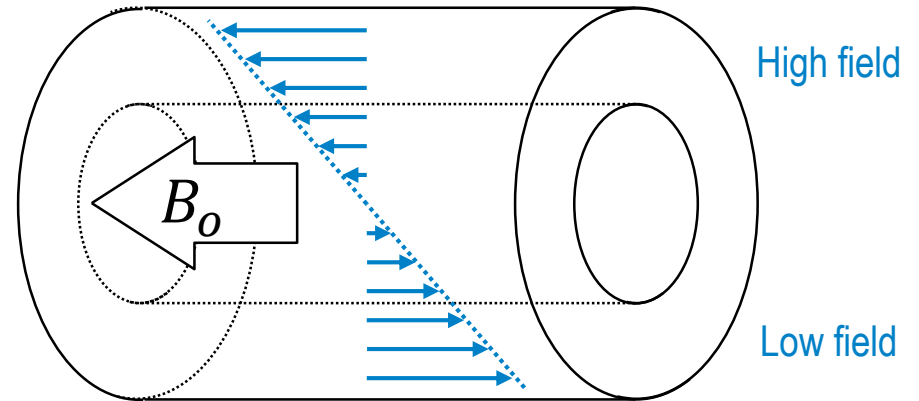
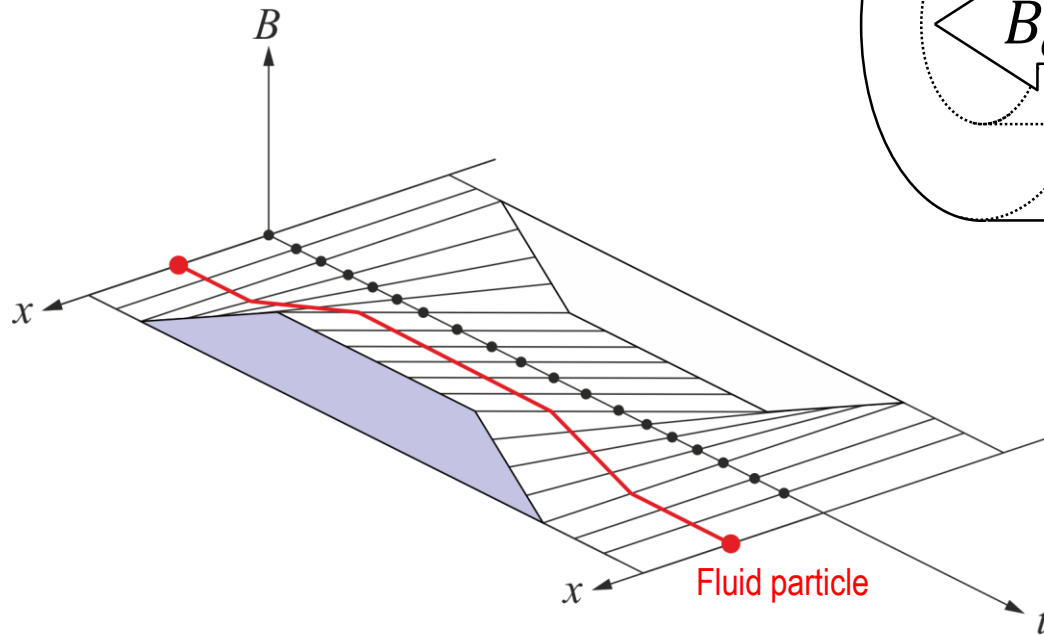




# Measuring Flow Velocity

## 1. MRI Principles

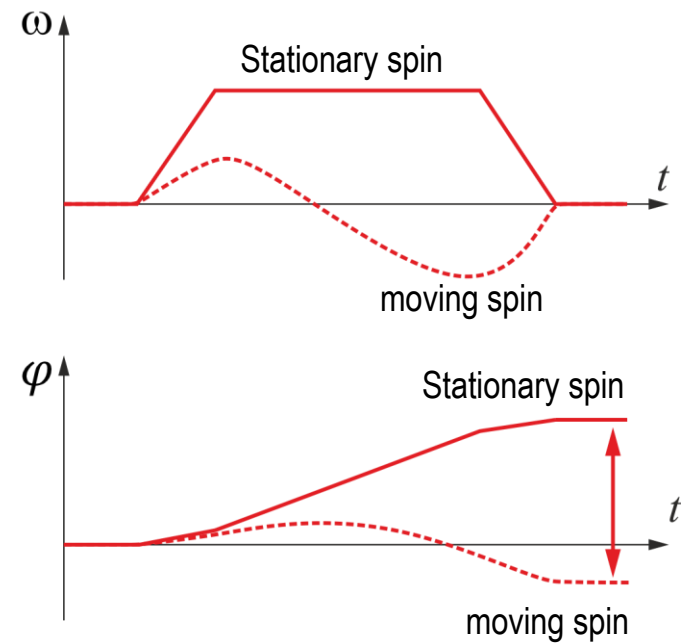
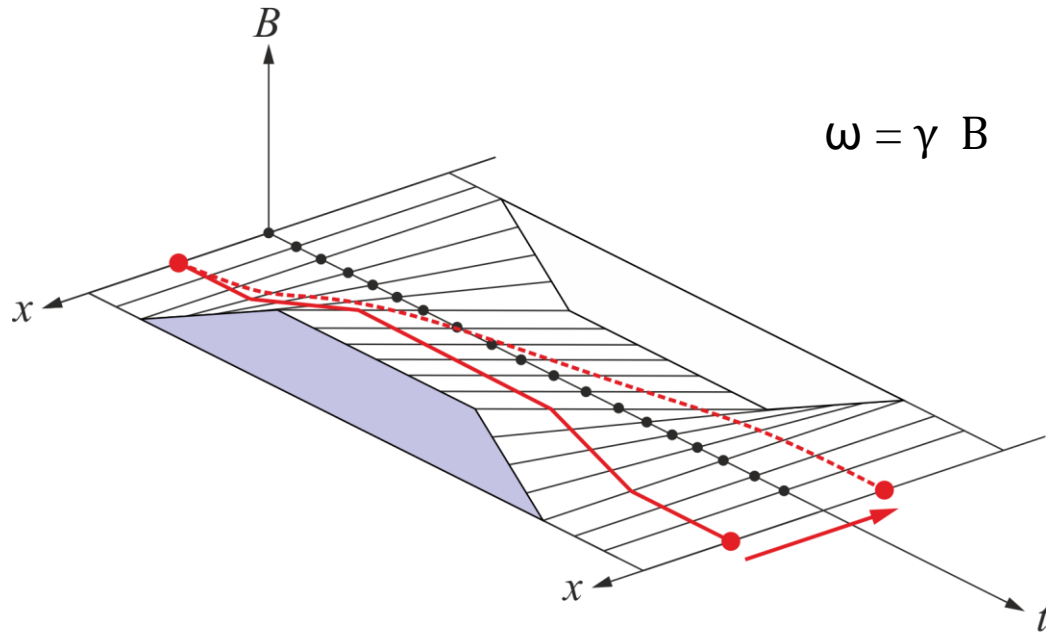
Magnetic gradient over time



# Measuring Flow Velocity

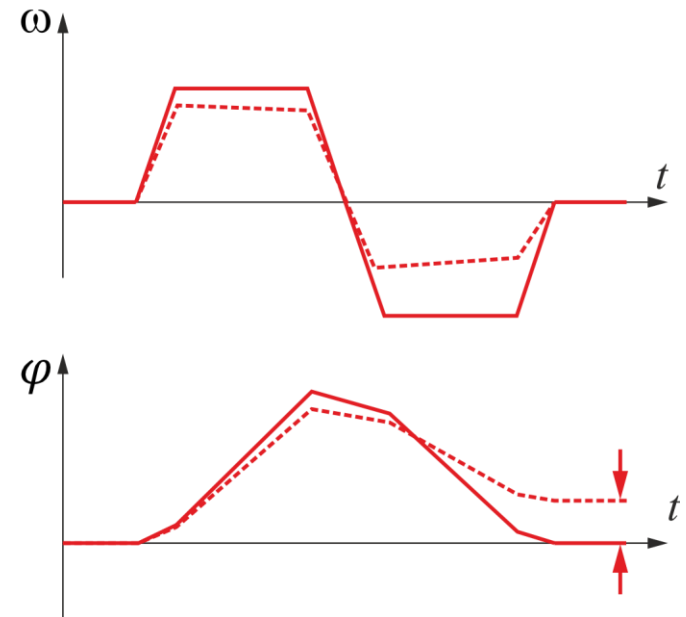
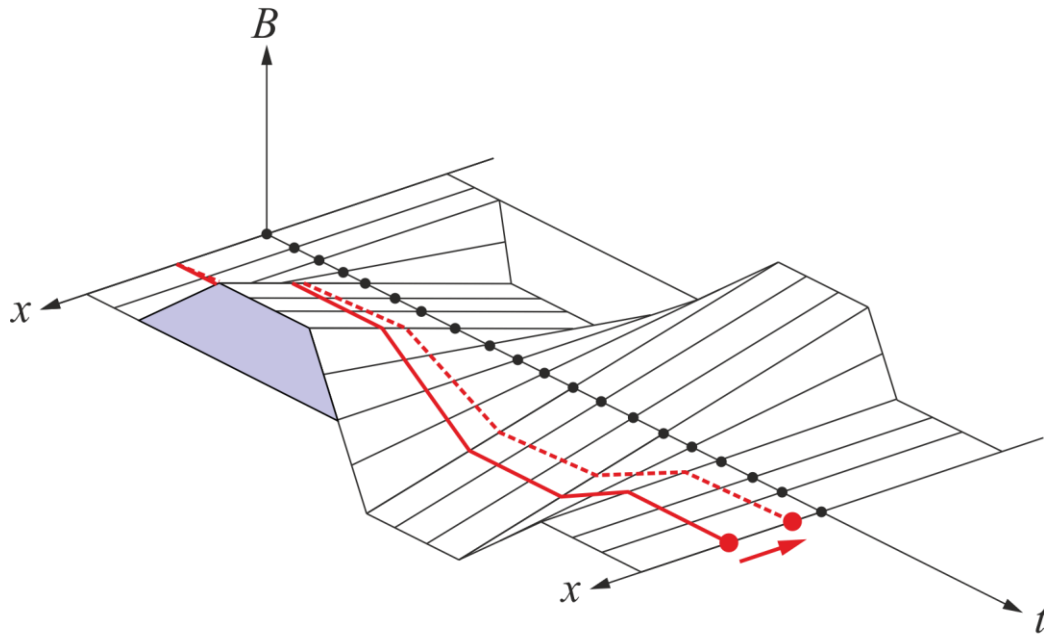
## 1. MRI Principles

### Magnetic gradient over time



# Measuring Flow Velocity

## 1. MRI Principles



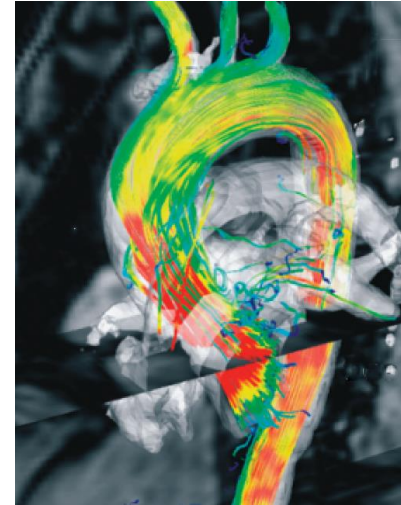
Linear relationship between residual phase angle and velocity

# Possibilities and Constraints in MRI

## 1. MRI Principles

### Possibilities

1. No optical access needed
2. Full 3D measurements within minutes
3. Simple post-processing (FFT)
4. Simultaneous measurement of fluid velocities and flow geometry.



# Possibilities and Constraints in MRI

## 1. MRI Principles

### Constraints

1. Danger because of magnetic field
2. Restrictions in materials
  - Model materials must be non-ferrous
  - Better no metals at all (antenna!)
  - Materials must have similar magnetic properties as the fluid, otherwise image distortions
3. Working fluid must have measurable spin, e.g. water



Most suitable material combination:

**Water + PMMA, POM, PA, ...**

Not suitable:

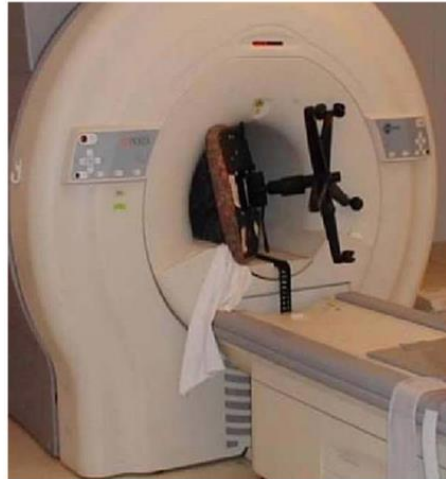
**Air, Metals, ...**

# Possibilities and Constraints in MRI

## 1. MRI Principles

### Constraints

4. Low temporal resolution compared to other measurement techniques
5. Relative new to engineering: not yet established in industry, only in academics

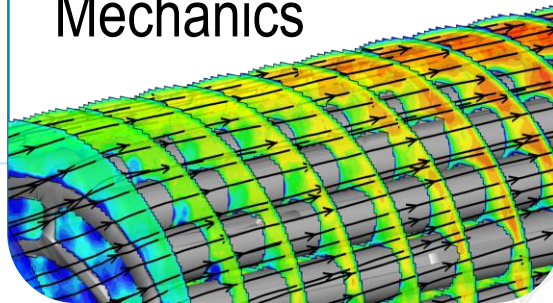


# Today's Agenda

## 1. MRI principles

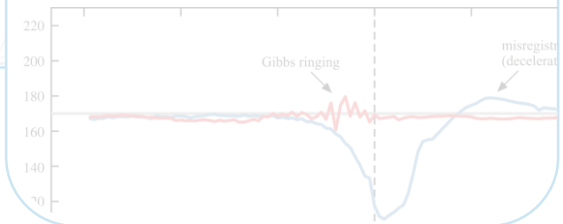


## 2. MRI in Fluid Mechanics



MRI Flow Lab

## 4. Measurement Errors in MRI



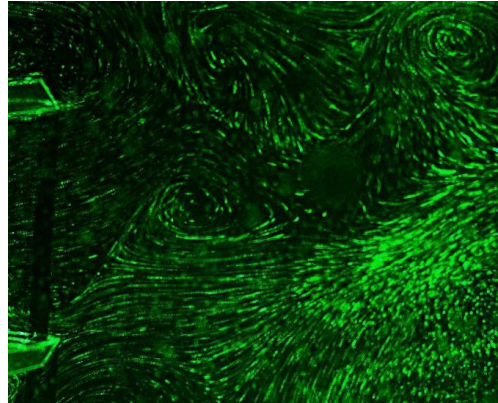
# Conventional Experiments vs. MRI

## 2. MRI in Fluid Mechanics

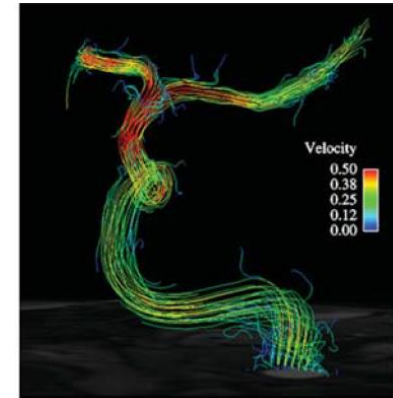
Probes



Laser-optical instruments



Flow MRI



Engine-realistic  
experiments

Engine-realistic  
experiments possible

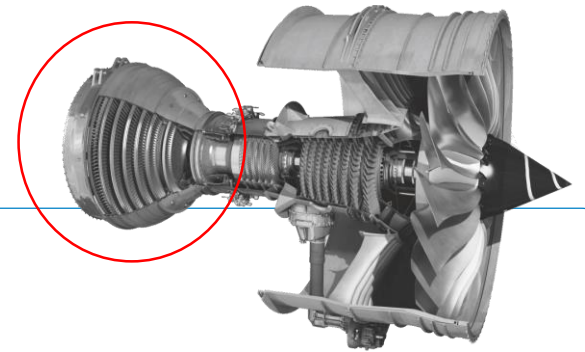
vs.

Quick simplified  
experiments

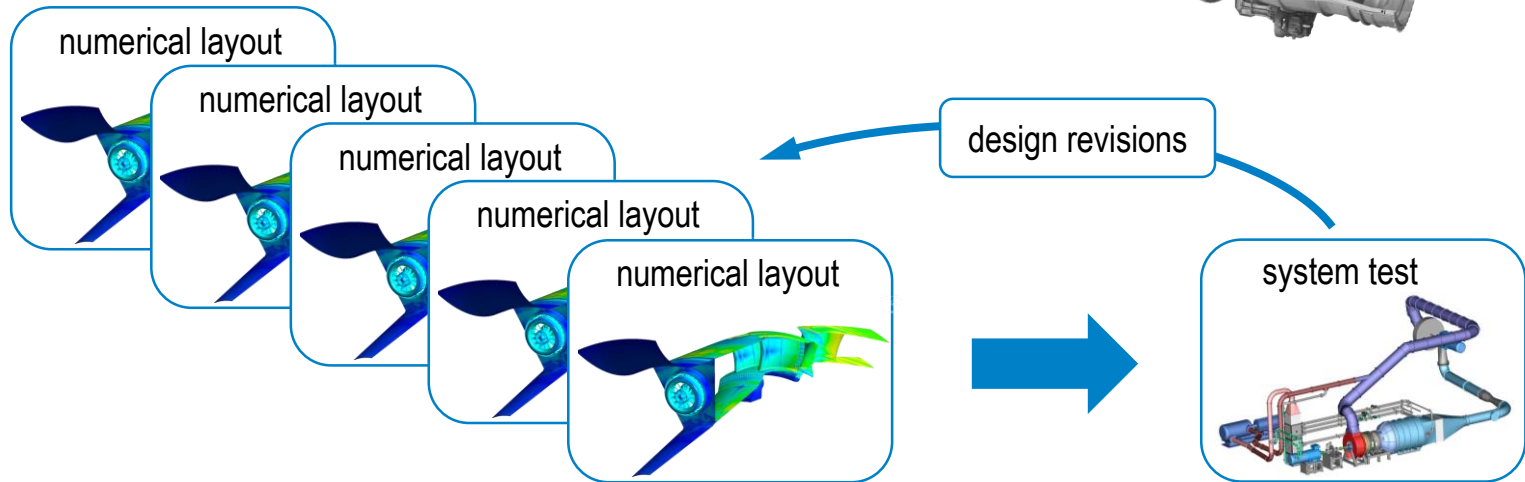


# Improving Flow Designs with MRI

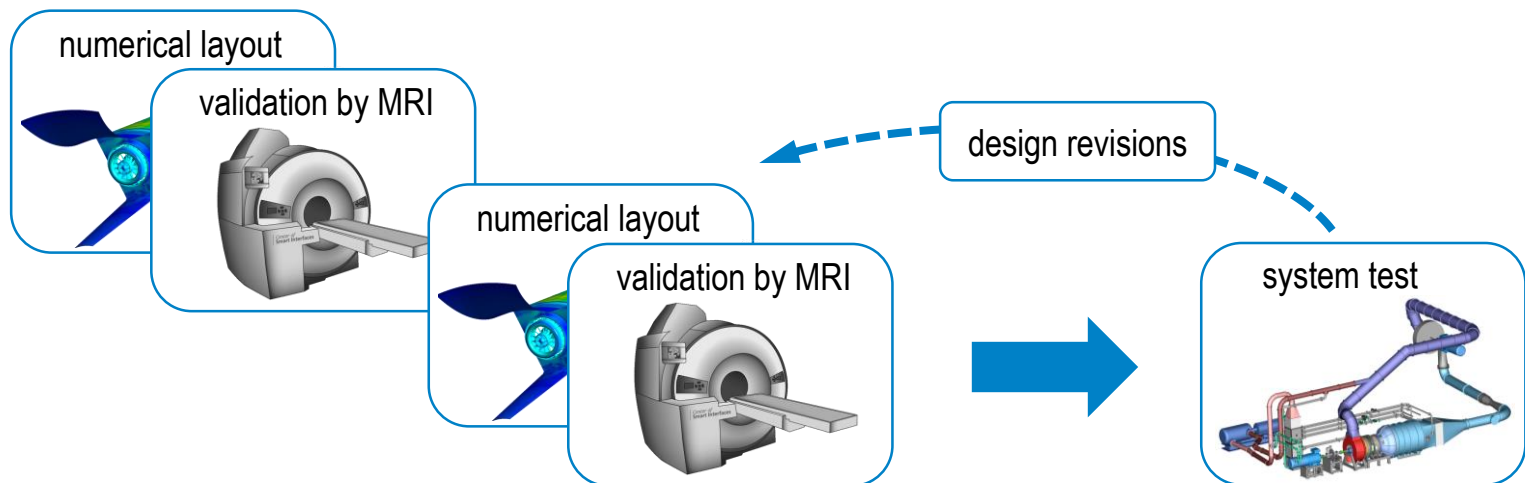
## 2. MRI in Fluid Mechanics



### Conventional design process



### Future?



# Implementation of MRI in Actual Design Processes

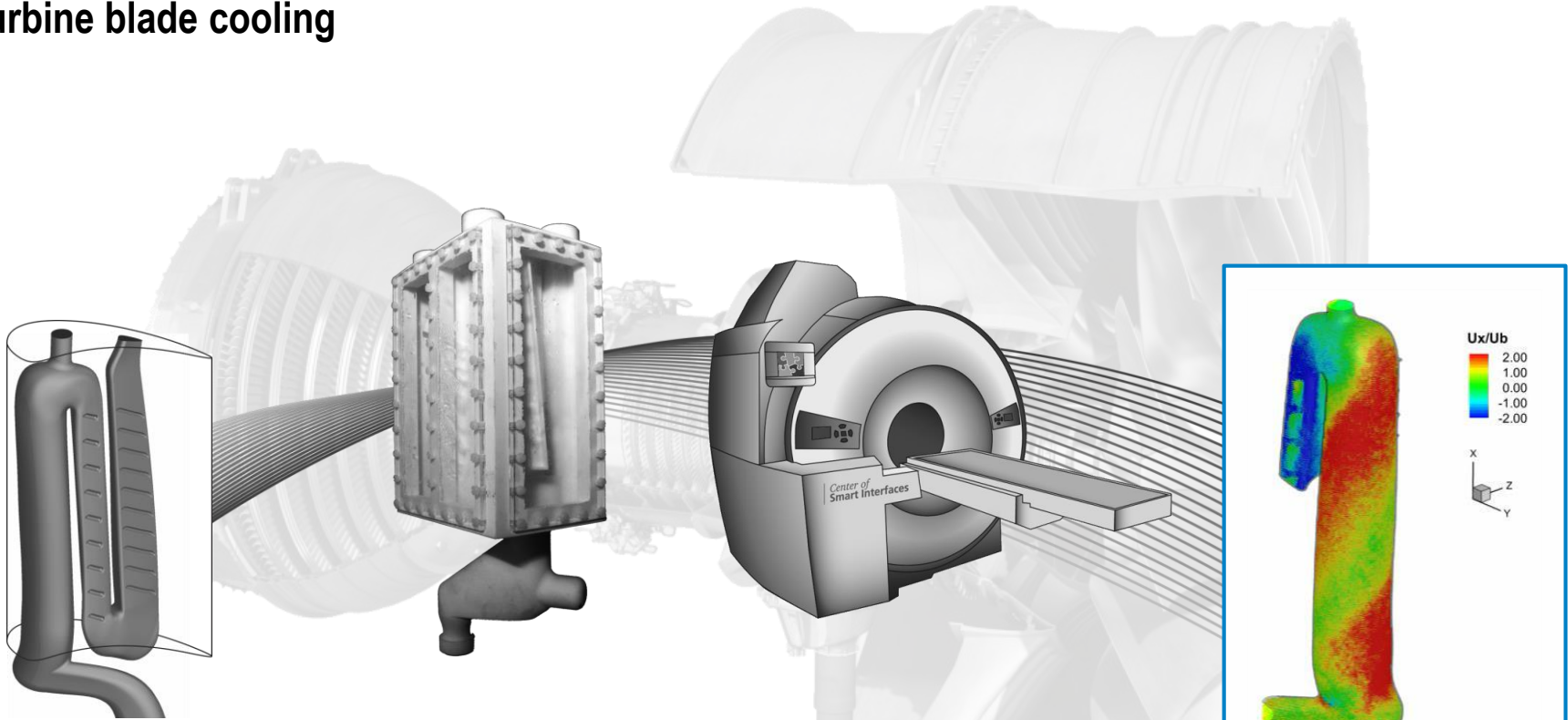
## 2. MRI in Fluid Mechanics



# Implementation of MRI in Actual Design Processes

## 2. MRI in Fluid Mechanics

### Turbine blade cooling



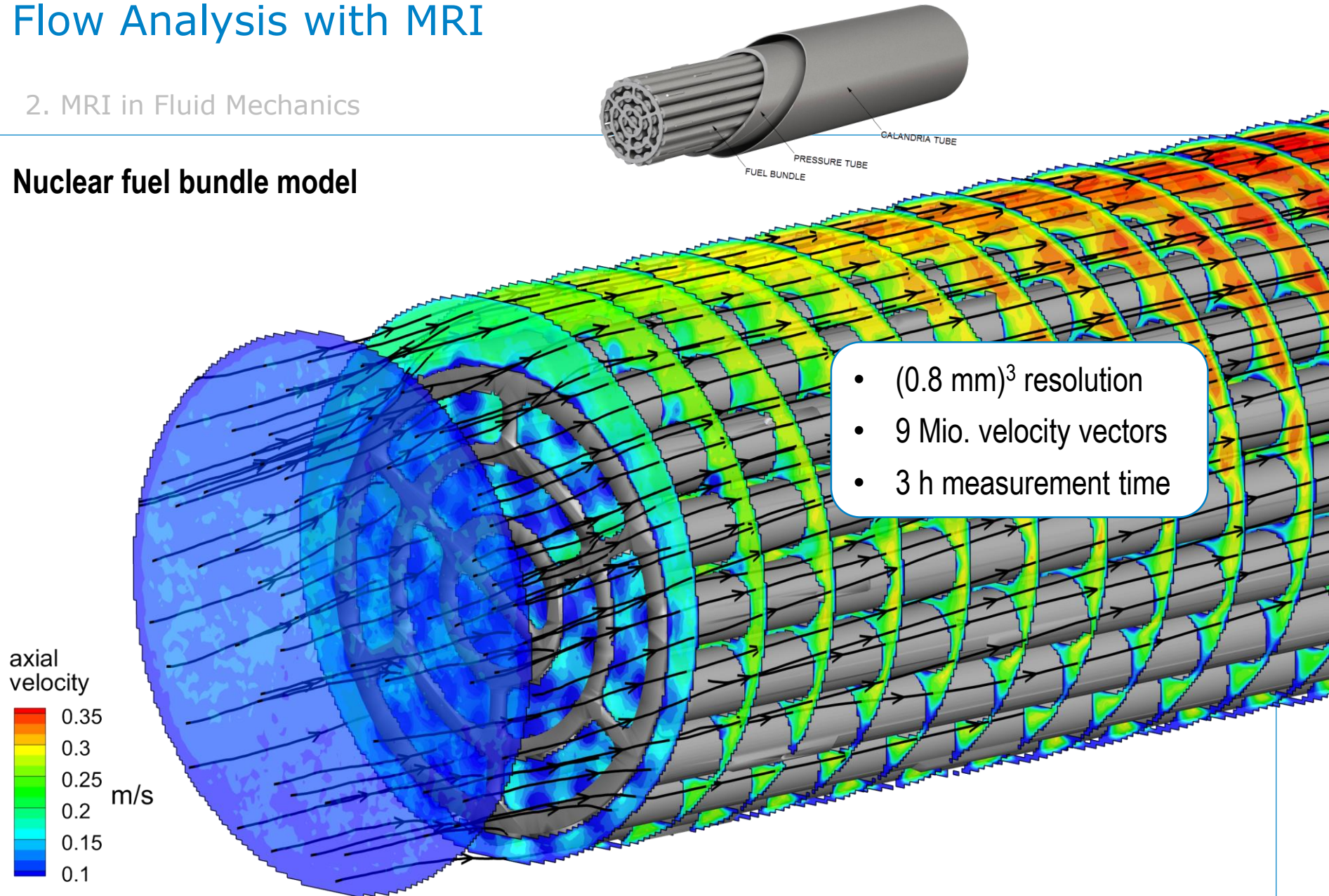
Rolls-Royce

< 5 days

# Flow Analysis with MRI

## 2. MRI in Fluid Mechanics

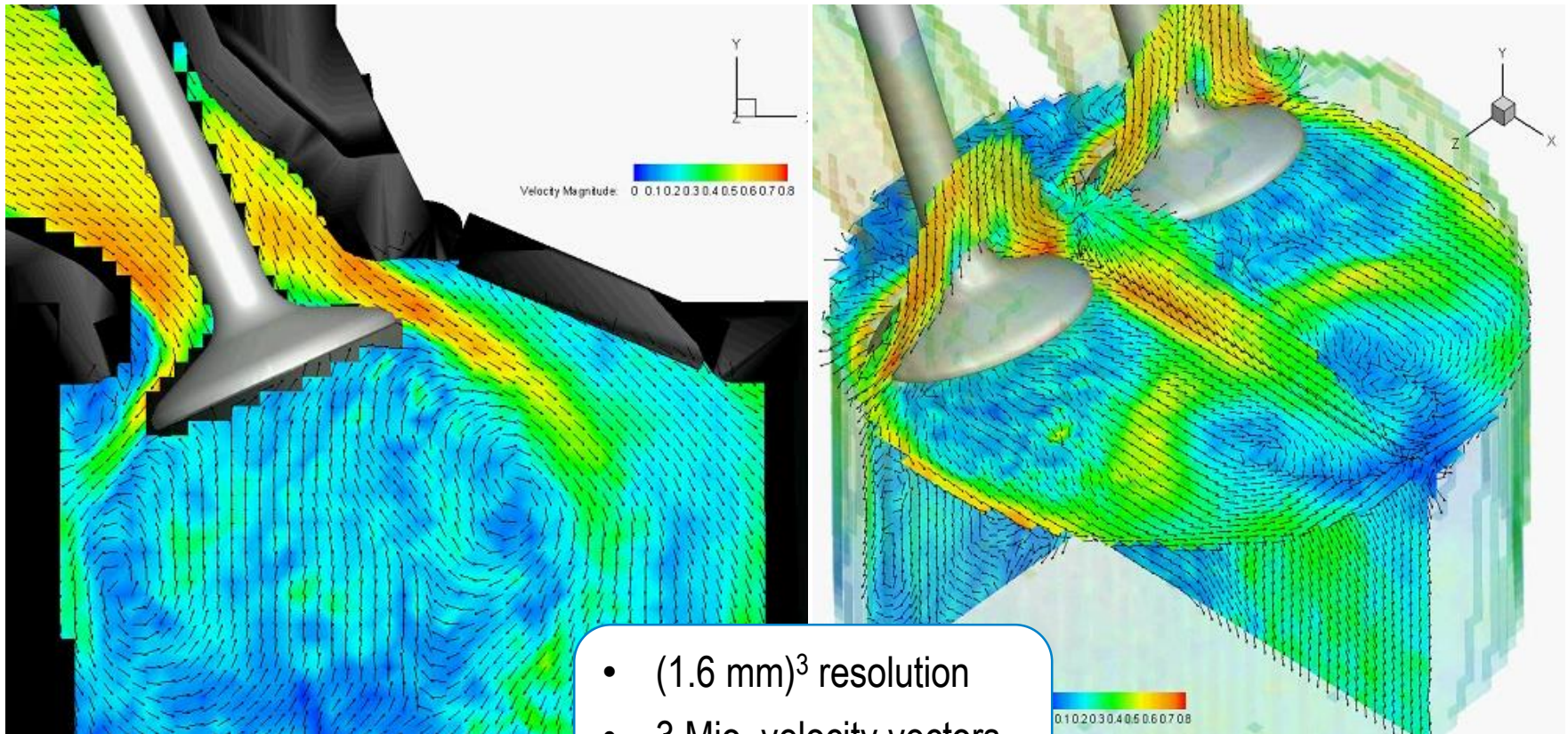
### Nuclear fuel bundle model



# Flow Analysis with MRI

## 2. MRI in Fluid Mechanics

### Periodic valve flow in IC engine models



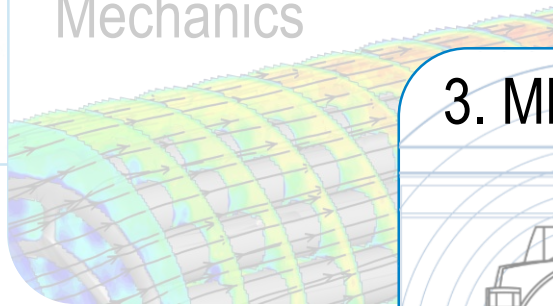
- $(1.6 \text{ mm})^3$  resolution
- 3 Mio. velocity vectors
- 1 h measurement time

# Today's Agenda

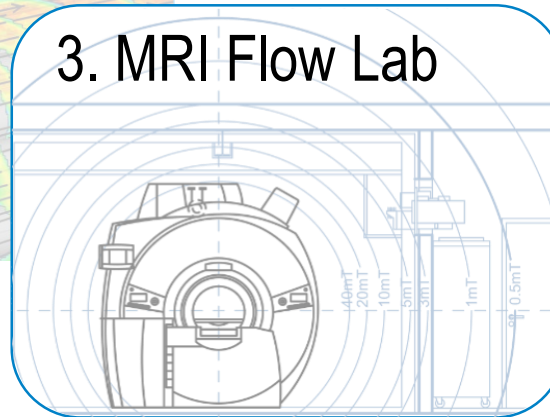
## 1. MRI principles



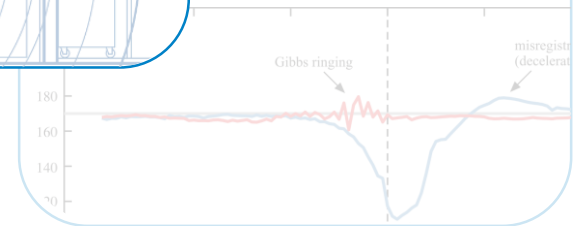
## 2. MRI in Fluid Mechanics



## 3. MRI Flow Lab



## Measurement in MRI



# A Dedicated Lab for Engineering

## 3. MRI Flow Lab

**2012 – 2016:** Precursory experiments at the University of Freiburg



# A Dedicated Lab for Engineering

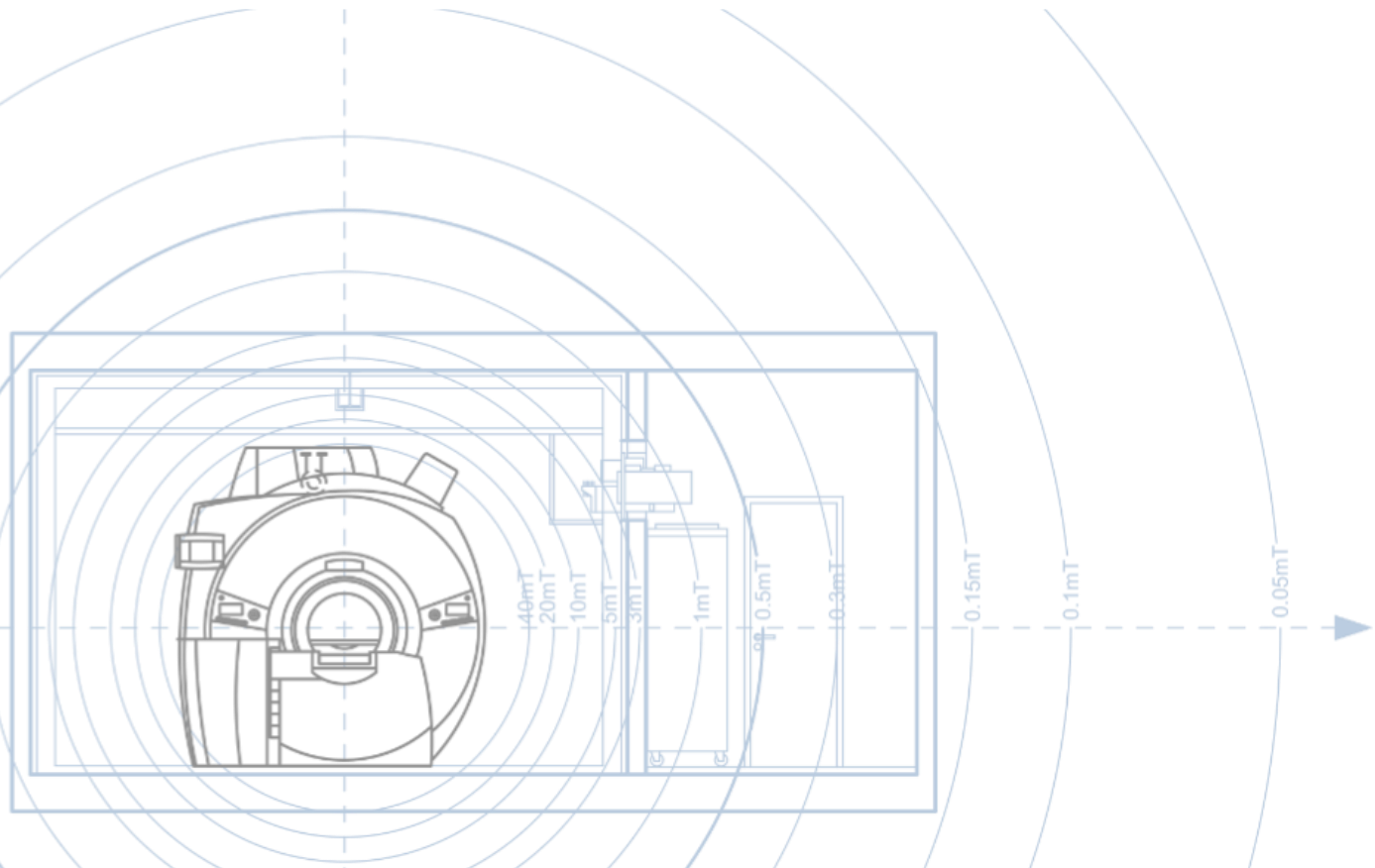
## 3. MRI Flow Lab

**2012 – 2016:**

Precursory experiments at the University of Freiburg

**Dec 2016:**

Approval and Funding





# A Dedicated Lab for Engineering

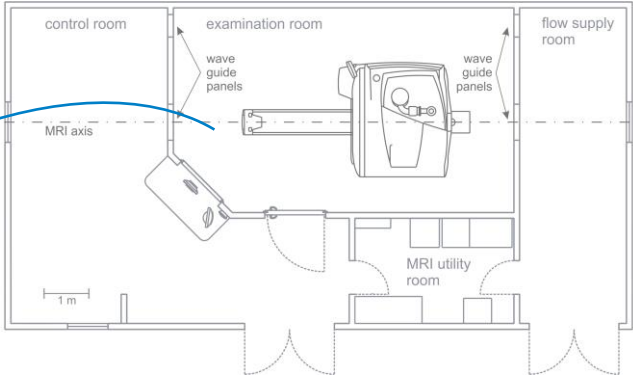
## 3. MRI Flow Lab

- 2012 – 2016:** Precursory experiments at the University of Freiburg
- Dec 2016:** Approval and Funding
- Jan 2018:** Completion of the laboratory



# Design Features

## 3. MRI Flow Lab



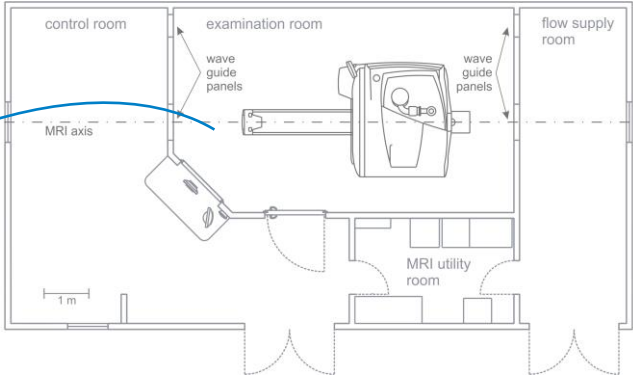
Examination room



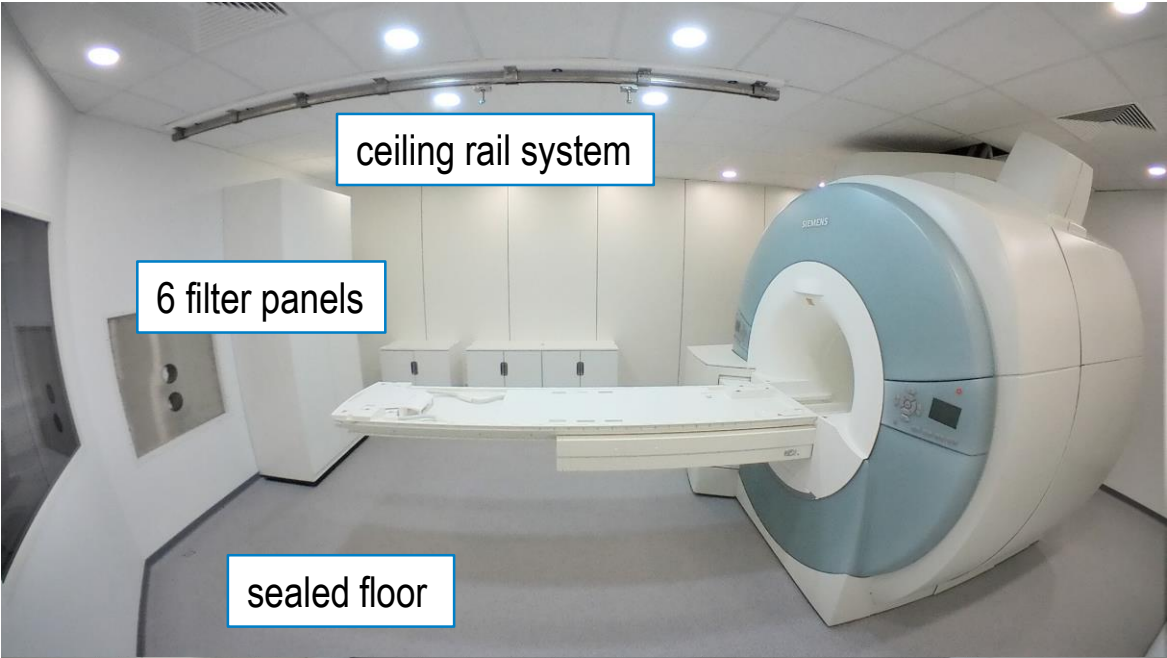
3T whole-body MRI scanner (Trio, Siemens)

# Design Features

## 3. MRI Flow Lab



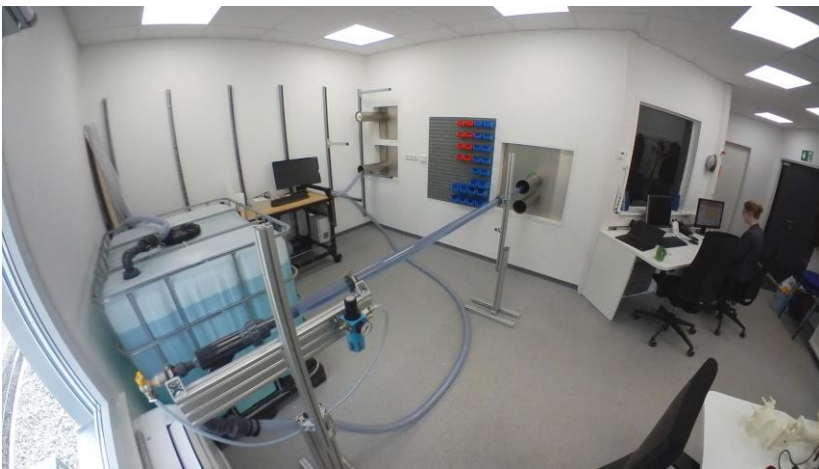
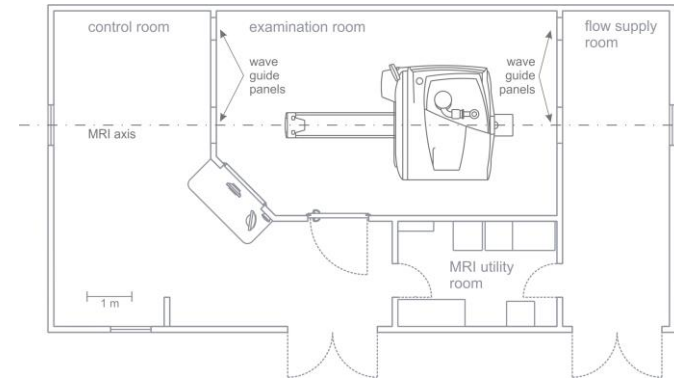
Examination room



# Flow Loop Installation

## 3. MRI Flow Lab

### Preliminary flow loop (200 L/min)

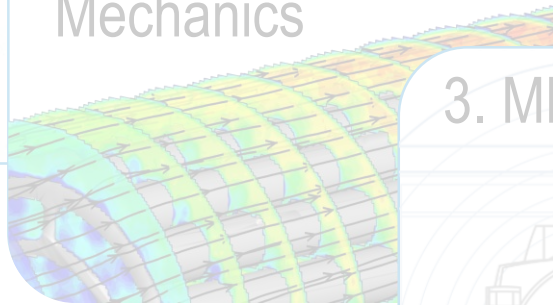


# Today's Agenda

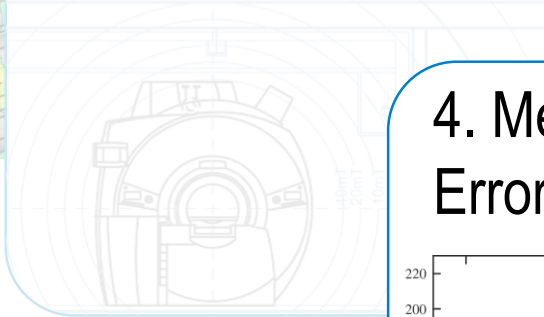
## 1. MRI principles



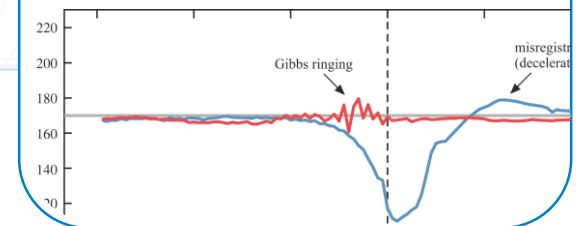
## 2. MRI in Fluid Mechanics



## 3. MRI Flow Lab



## 4. Measurement Errors in MRI

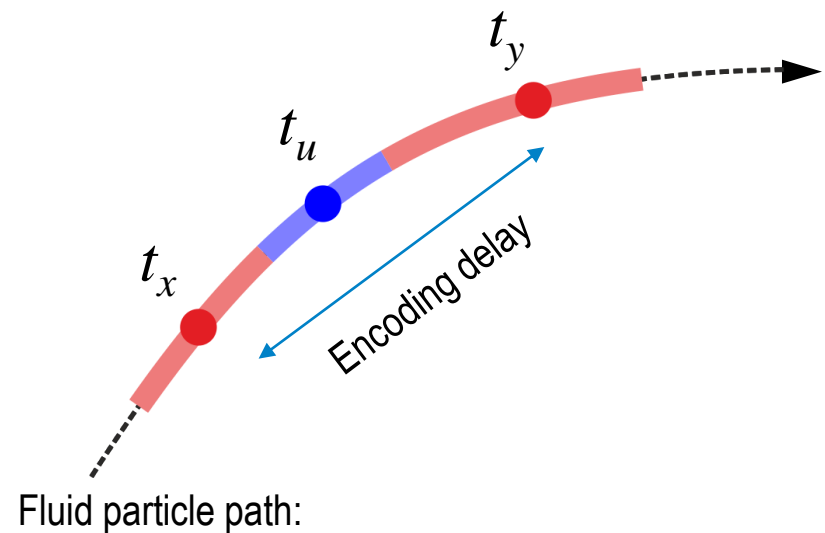
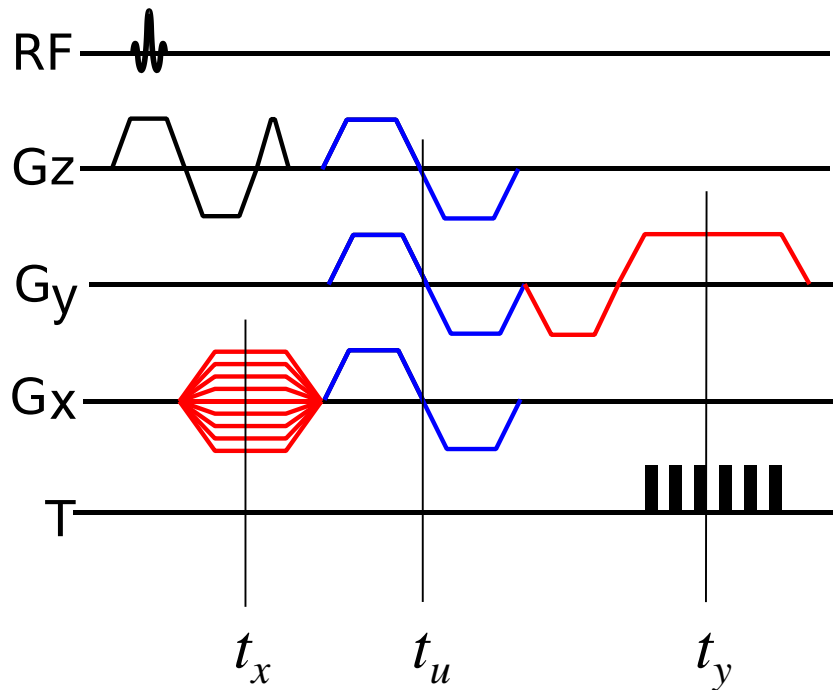


# Systematic Measurement Errors

## 4. Measurement Errors in MRI

### Example: flow induced misregistration

Conventional MRI sequence:



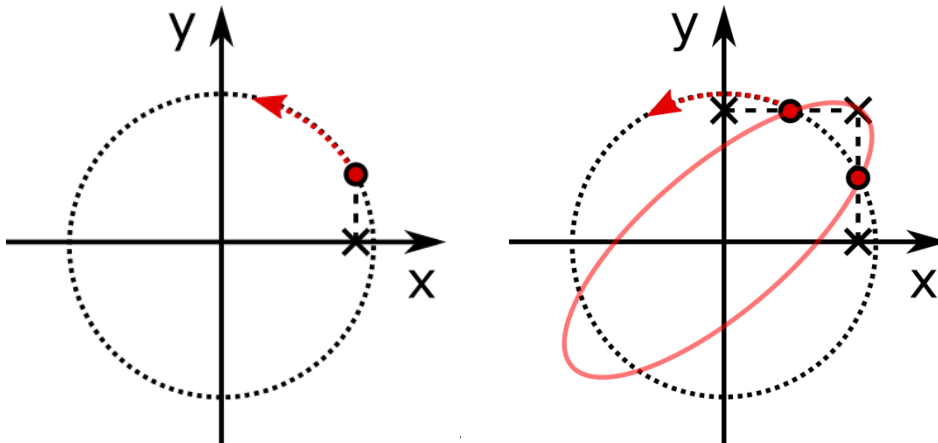
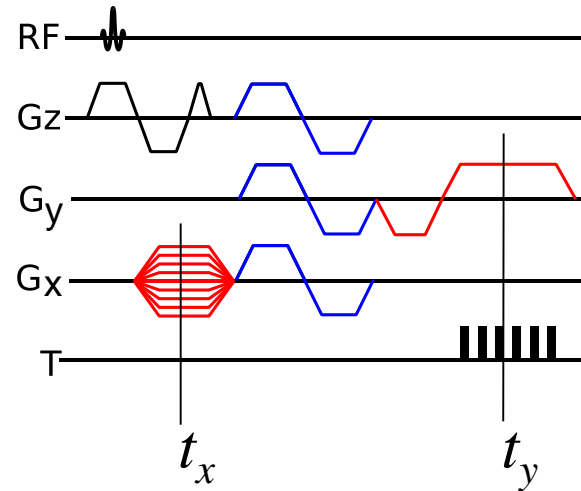
1 m/s flow velocity and  
2 ms encoding delay  
→ 2 mm misregistration

# Systematic Measurement Errors

## 4. Measurement Errors in MRI

### Manifestation of misregistration

- Example: Circular motion



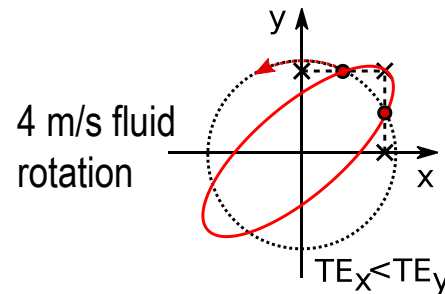
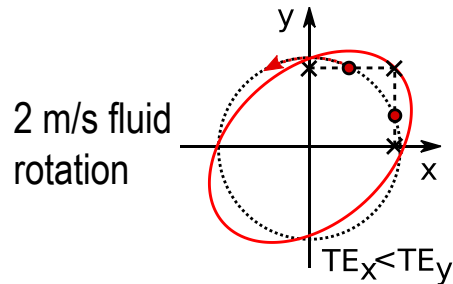
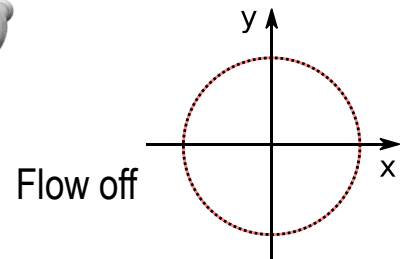
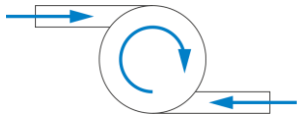
Removing misregistration  
by synchronizing all  
encoding events

# Pulse Sequence Design – Better Accuracy

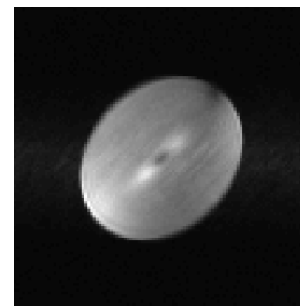
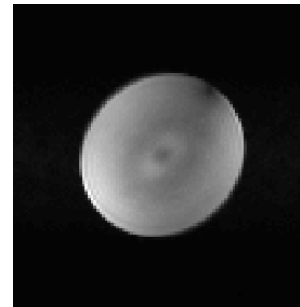
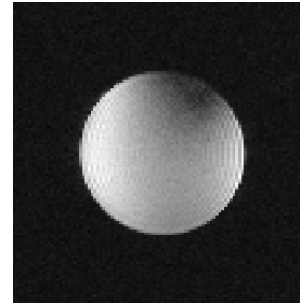
## 4. Measurement Errors in MRI

### Experimental confirmation

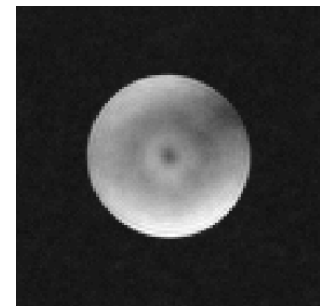
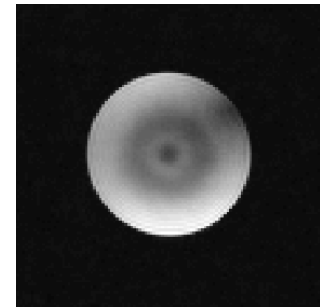
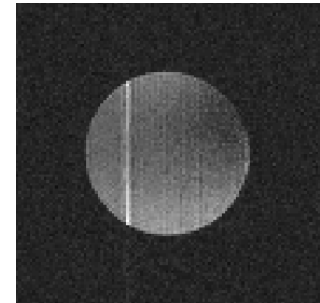
- Swirl flow test case



### Conventional MRI



### Improved Sequence



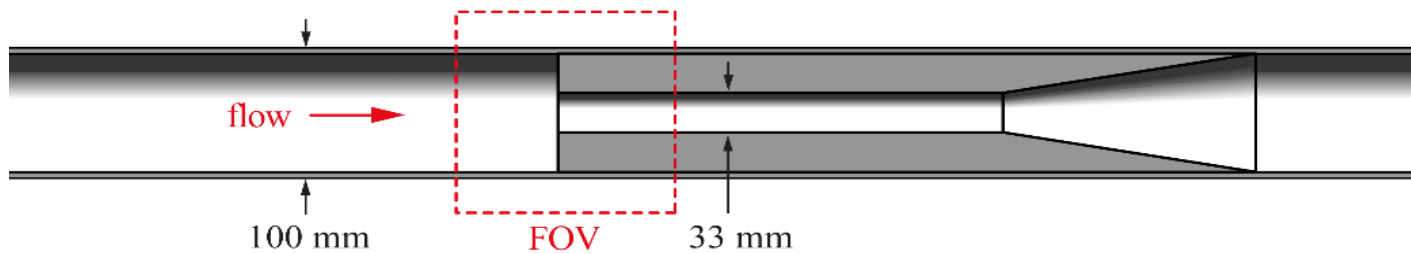


# Pulse Sequence Design – Better Accuracy

## 4. Measurement Errors in MRI

### Experimental Confirmation

- Flow contraction test case

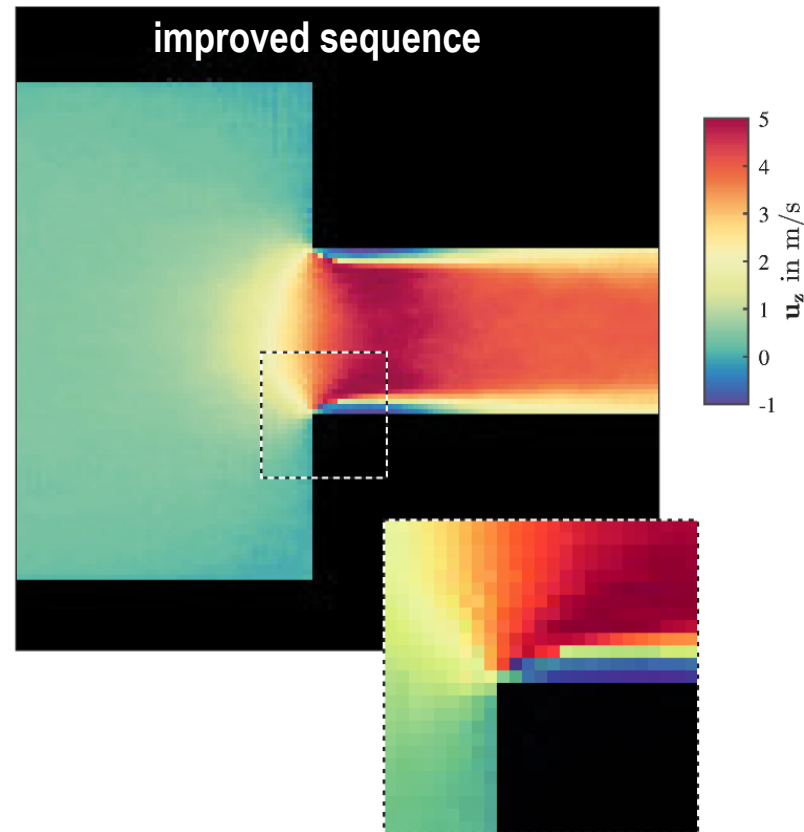
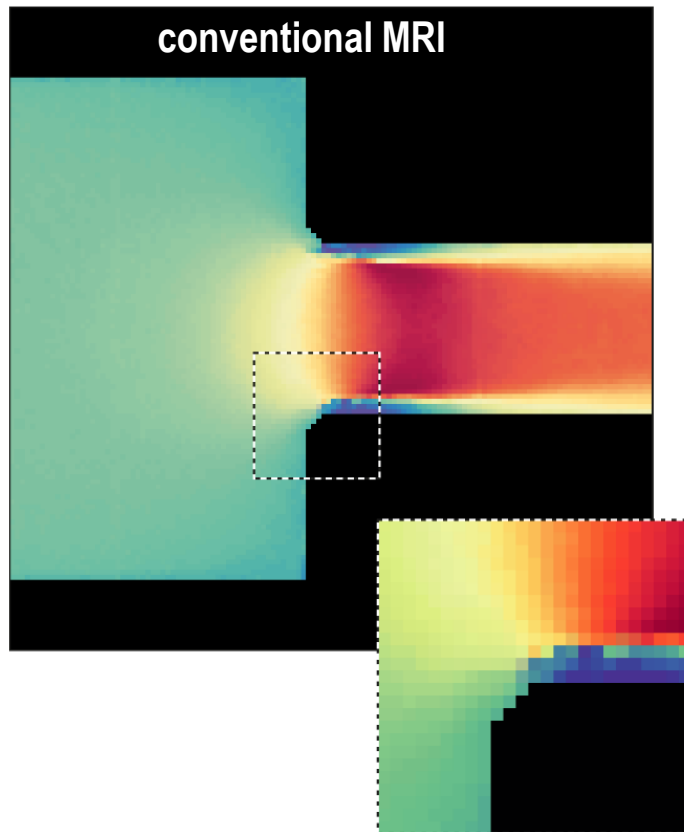
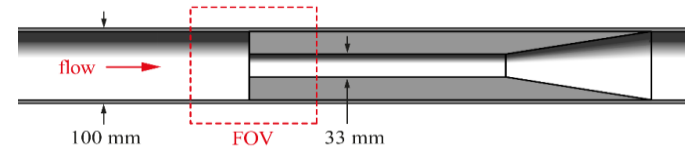


# Pulse Sequence Design – Better Accuracy

## 4. Measurement Errors in MRI

### Experimental Confirmation

- Flow contraction test case

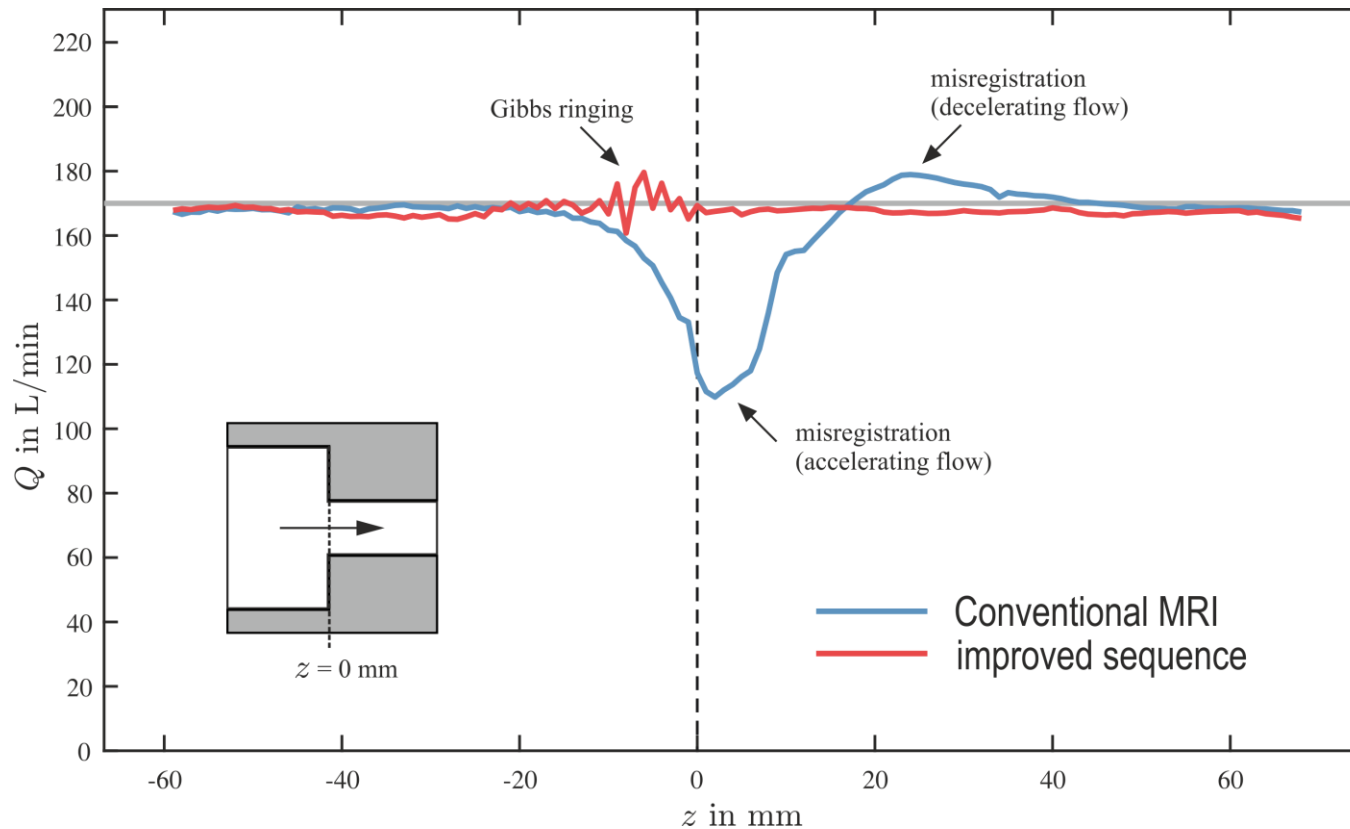
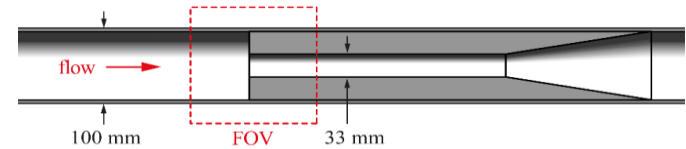


# Pulse Sequence Design – Better Accuracy

## 4. Measurement Errors in MRI

### Experimental Confirmation

- Flow contraction test case



# MRI Flow Lab

from Medicine to Engineering

*Thank You*

