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► **To cite this version:**

Feryal Guerroudj, Laouès Guendouz, Jean-Marc Commenge, Rainier Hreiz, N. Louvet, et al.. NMR methods and devices for the characterization of flows and transfers in milli-channels. European Conference on Magnetic Resonance (EUROMAR 2022), Jul 2022, Utrecht, Netherlands. hal-03774601

**HAL Id: hal-03774601**

**<https://hal.science/hal-03774601>**

Submitted on 12 Sep 2022

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# NMR methods and devices for the characterization of flows and transfers in milli-channels

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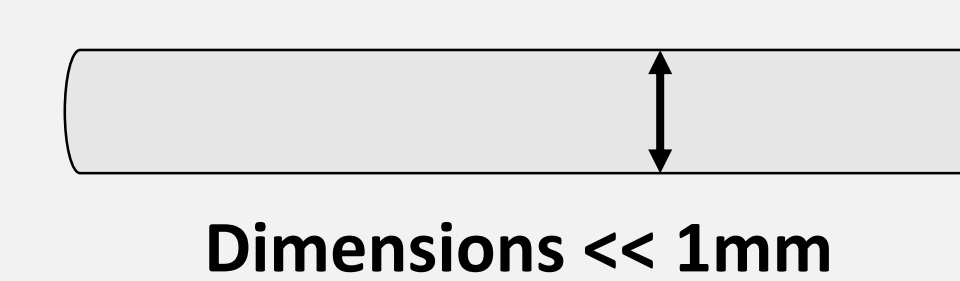
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## 1. Introduction

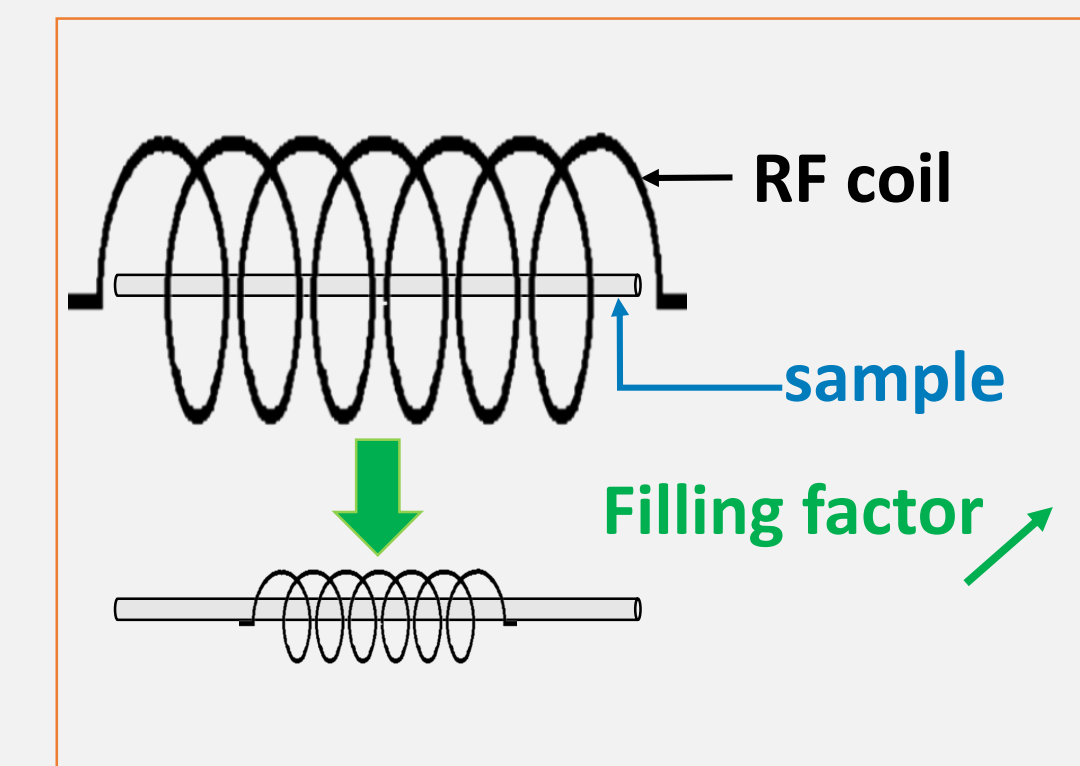
- Milli-fluidics is the technology of flows in channels with characteristic dimensions of a few hundred microns
- Reducing the dimensions of the systems affects the equilibrium of the forces and generates a specific behavior of the flow<sup>1</sup>
- Milli-fluidic systems are implemented in different fields such as synthesis chemistry, biology or process engineering<sup>2</sup>
- The geometrical complexity of the systems induces a limits the use of optical characterization methods
- NMR methods are adapted to such systems (geometries and materials)<sup>3</sup> provided that the measurement sensitivity is improved<sup>4,5</sup>



➤ Approach: development of radiofrequency (RF) milli-coils<sup>6</sup> for emission and reception of the NMR signal

In this study

- We developed adapted methods for the characterization of flows in milli-fluidic systems by NMR/MRI
  - Increase the sensitivity by developing RF coils
  - Optimize imaging parameters
- We applied these methods in two study cases:
  - Characterize the hydrodynamics in micro-mixer
  - Visualize a biofilm development in a capillary

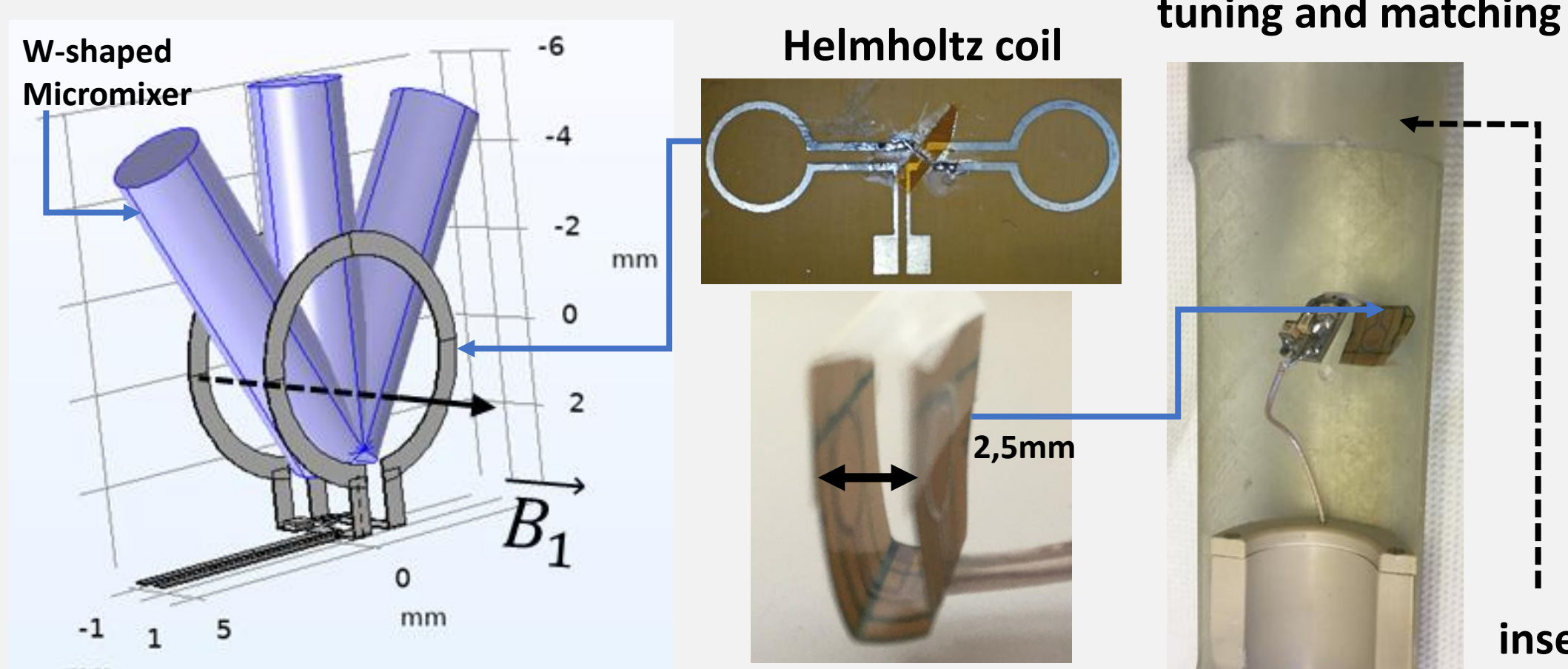


## 2. Materials and methods

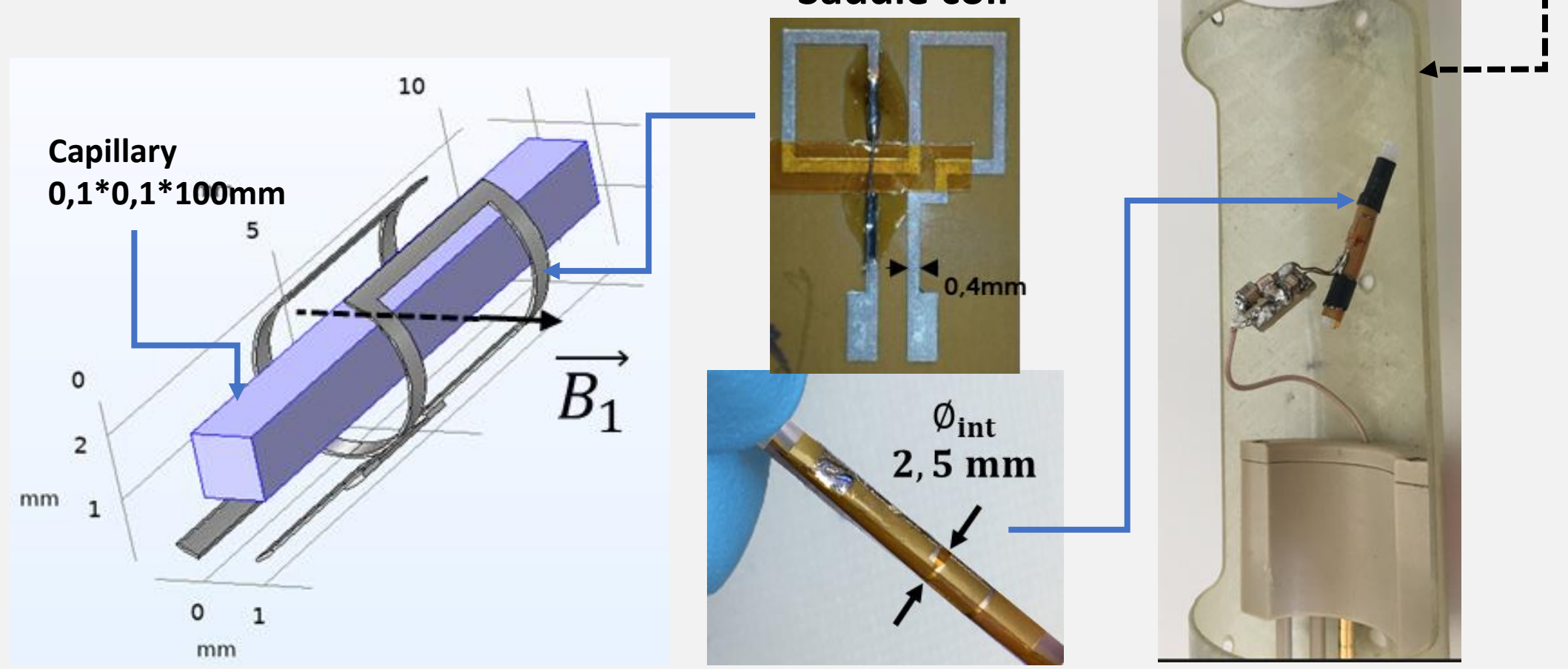
### Fabrication of RF milli-coils

Etching on DuPont™ Pyralux® AC substrate

Chosen geometry for application 3.a

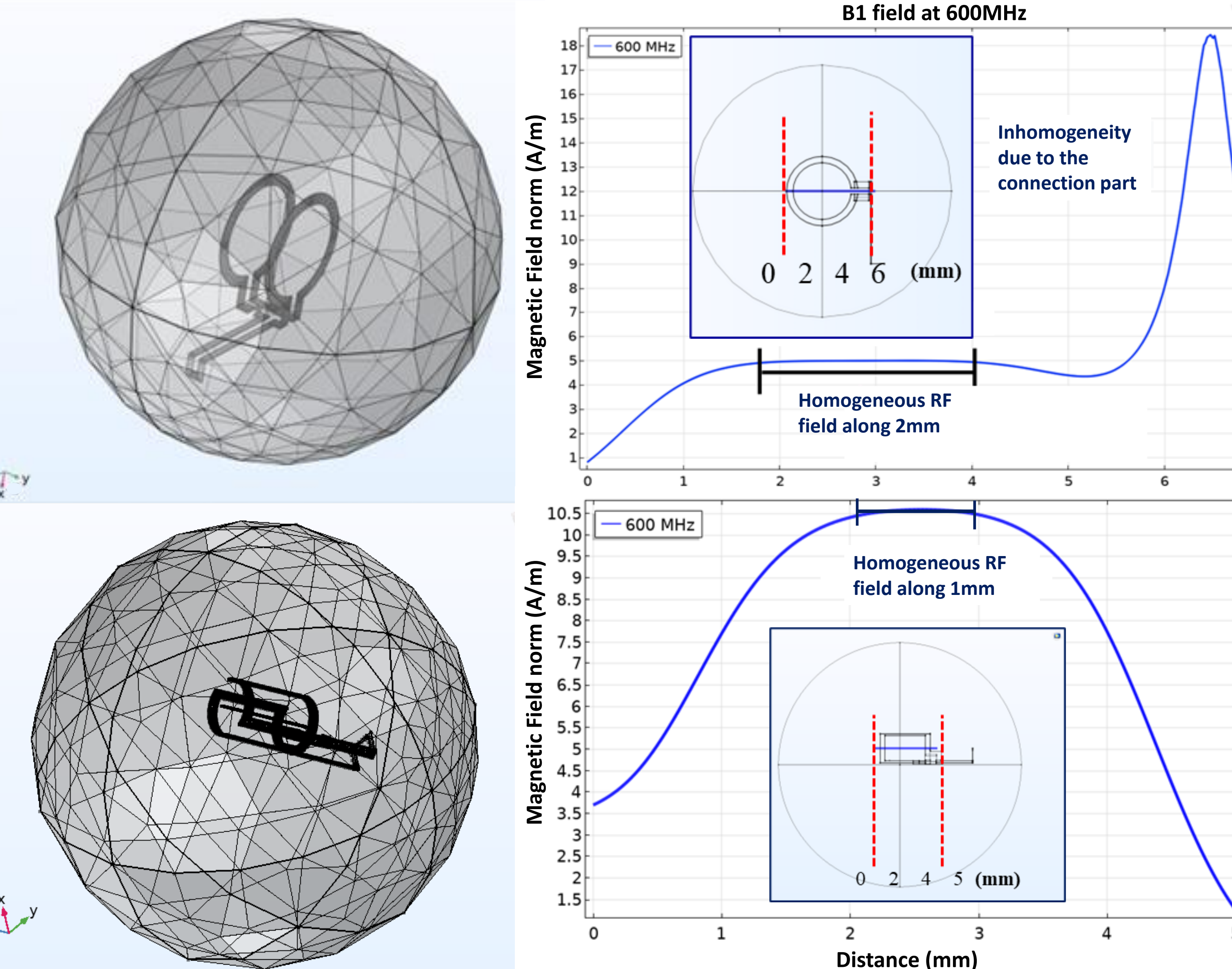


Chosen geometry for application 3.b



### RF simulations on COMSOL Multiphysics®

Physics : Radiofrequency and electromagnetic wave  
Calculation: Mesh generated by the finite element method

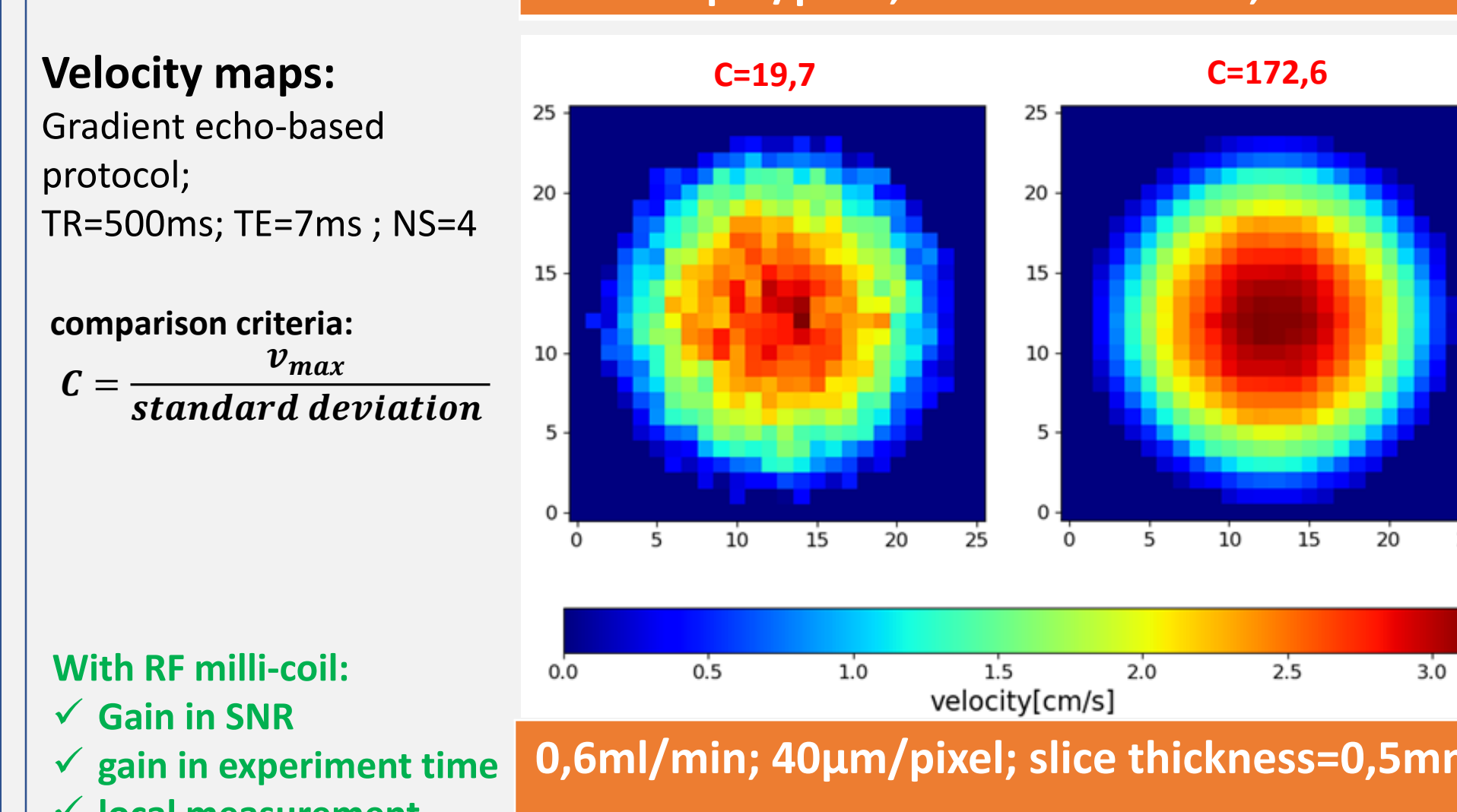
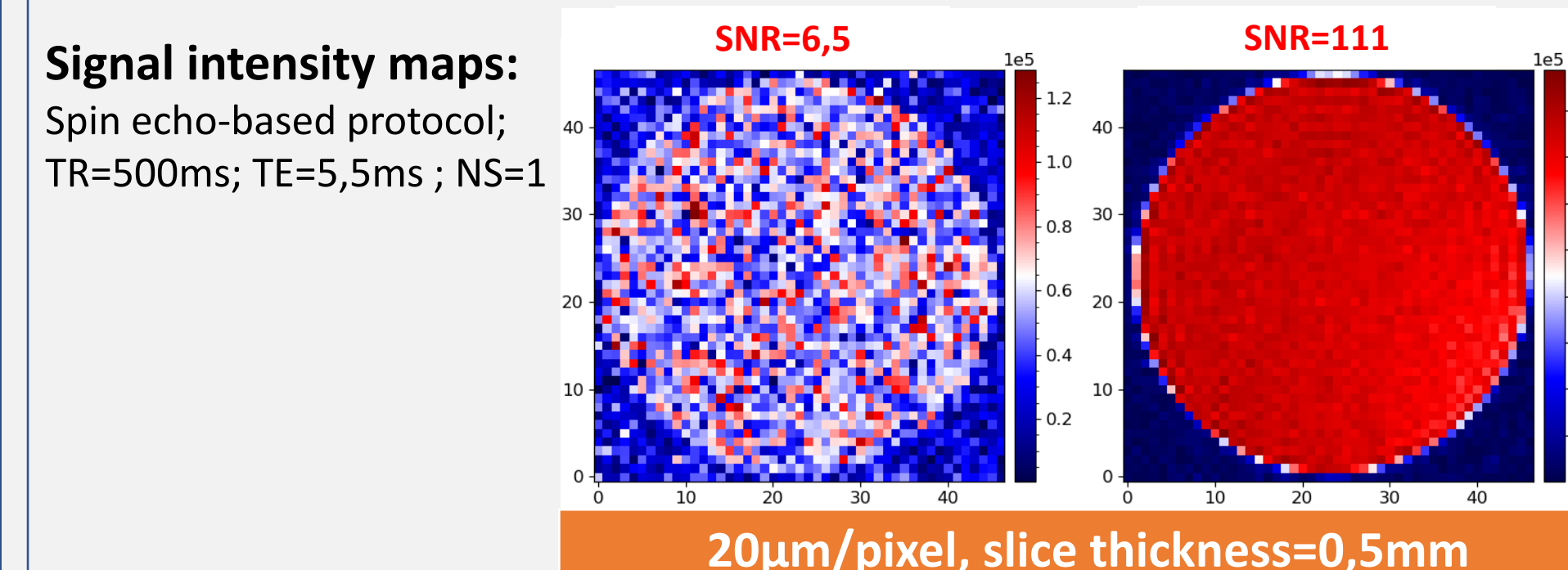


### Qualification

Comparison measurements between a commercial probe (Bruker MicWB40 1H, 25mm ID) and the fabricated milli-coil



Sample: Capillary 0,9mm ID + CuSO<sub>4</sub> solution (T<sub>1</sub> = 100ms)



comparison criteria:  
 $C = \frac{v_{max}}{standard\ deviation}$

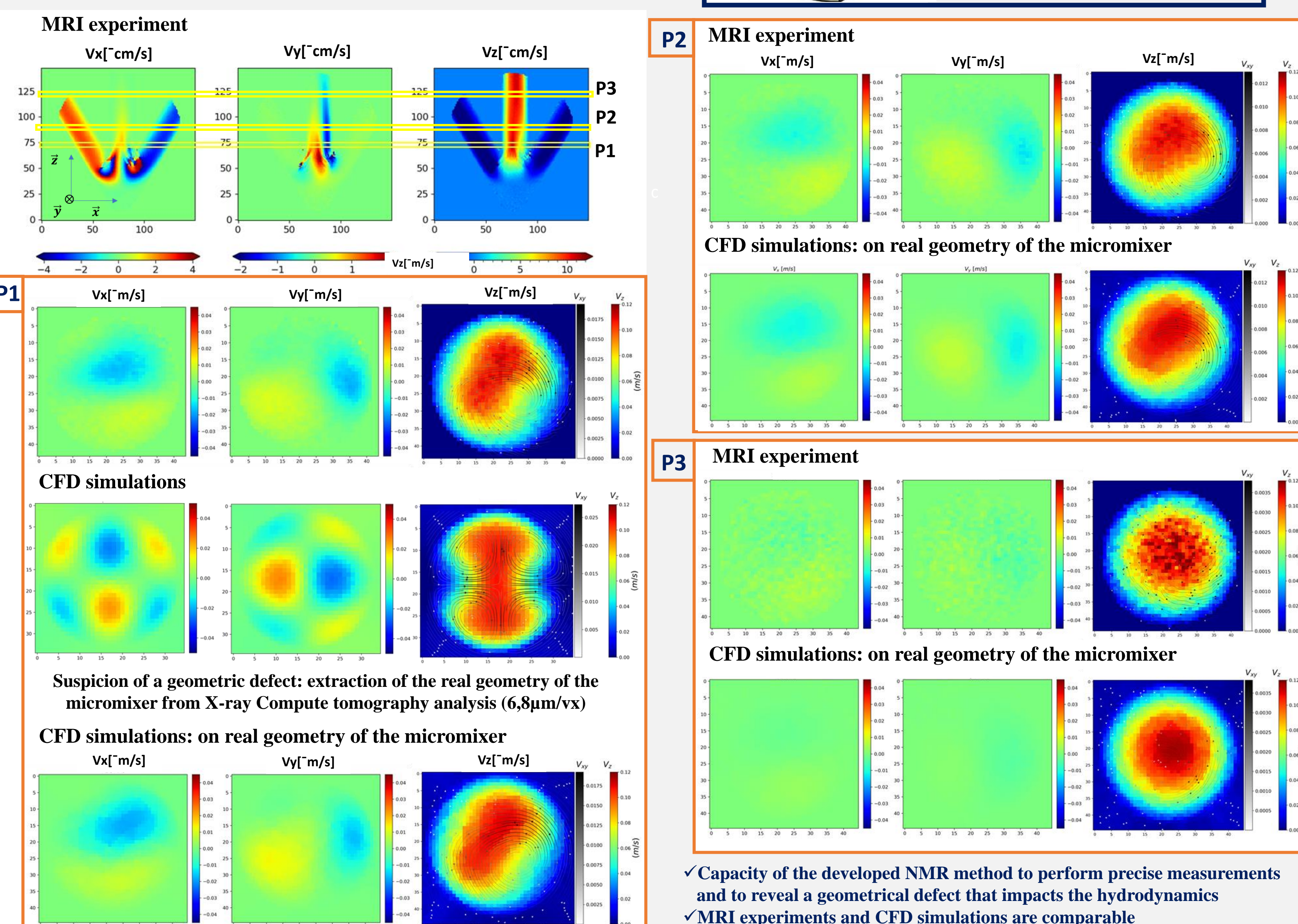
- With RF milli-coil:
  - ✓ Gain in SNR
  - ✓ gain in experiment time
  - ✓ local measurement

## 3. Results

### a. MRI study of the hydrodynamics in micro-mixers

- Characterization of hydrodynamics instabilities in a W-shaped micromixer (Re per entry ~ 100 ) by a coupled approach :
  - ✓ MRI measurements
  - ✓ Numerical simulations<sup>7</sup> (CFD- Ansys Fluent)
- Comparison of the two approaches
- Validation of the numerical simulations

Fluid/entry	CuSO <sub>4</sub> solution (T <sub>1</sub> = 100ms)
Re/entry	60 to 170
Slice thickness	0,2mm
Resolution	24μm/pixel
MRI protocol	Gradient echo;; TE=5,5ms



✓ Capacity of the developed NMR method to perform precise measurements and to reveal a geometrical defect that impacts the hydrodynamics  
✓ MRI experiments and CFD simulations are comparable

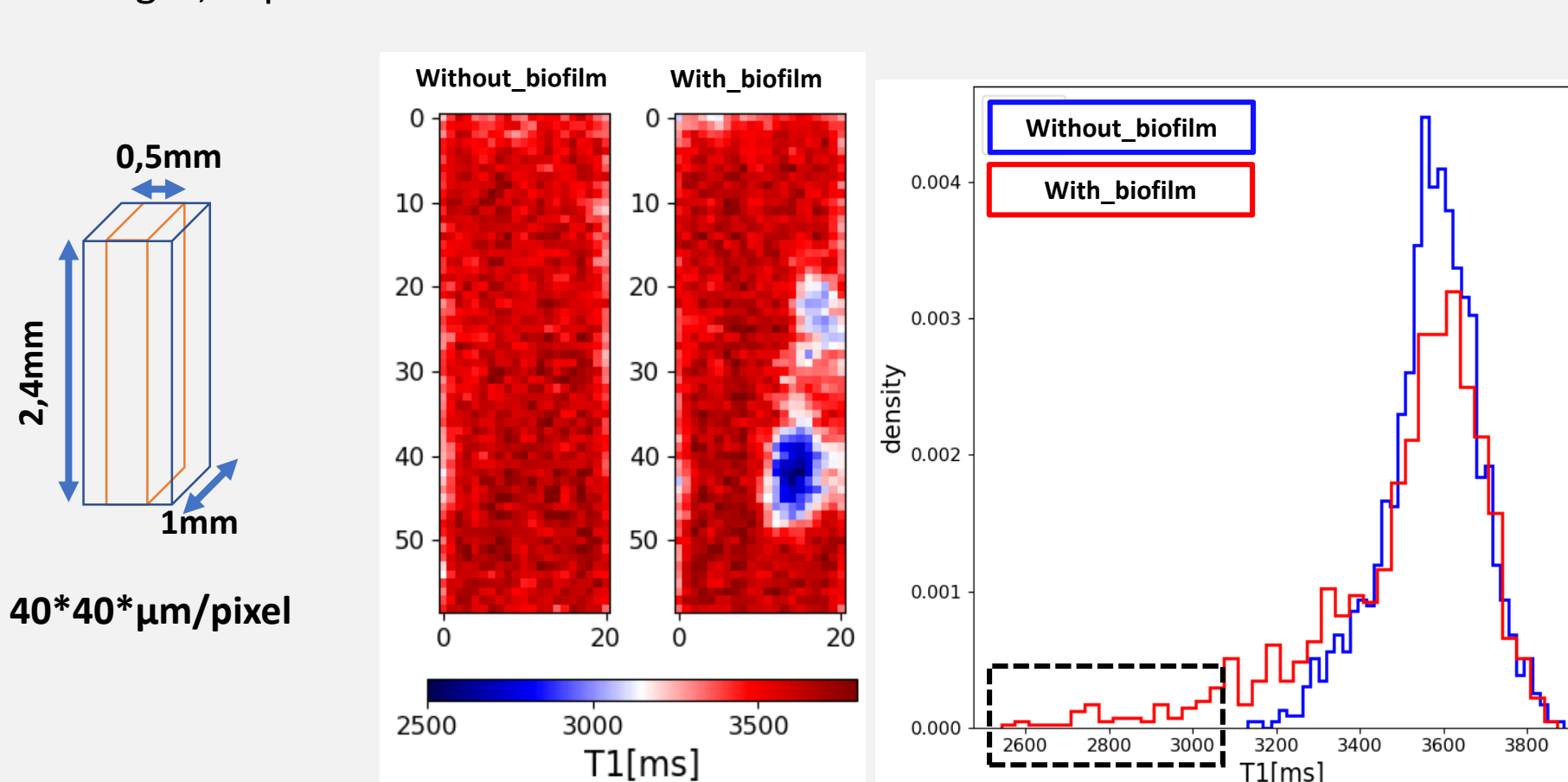
### b. MRI visualization of a biofilm development in a capillary

- perform a biofilm growth experiment in a capillary of submillimeter dimensions (pore model)
- MRI visualization of a biofilm and its impact on the hydrodynamics<sup>8,9</sup>

Protocol for biofilm culture:  
- bacteria: shewanella oneidensis (soil model)  
- adhesion stage: colonize the capillary with the bacterial culture during 4h at ambient temperature (flow 1.2ml/min, ; in closed-loop)  
- biofilm culture stage: continuous feeding with nutrient solution (flow rate 1.2ml/min)

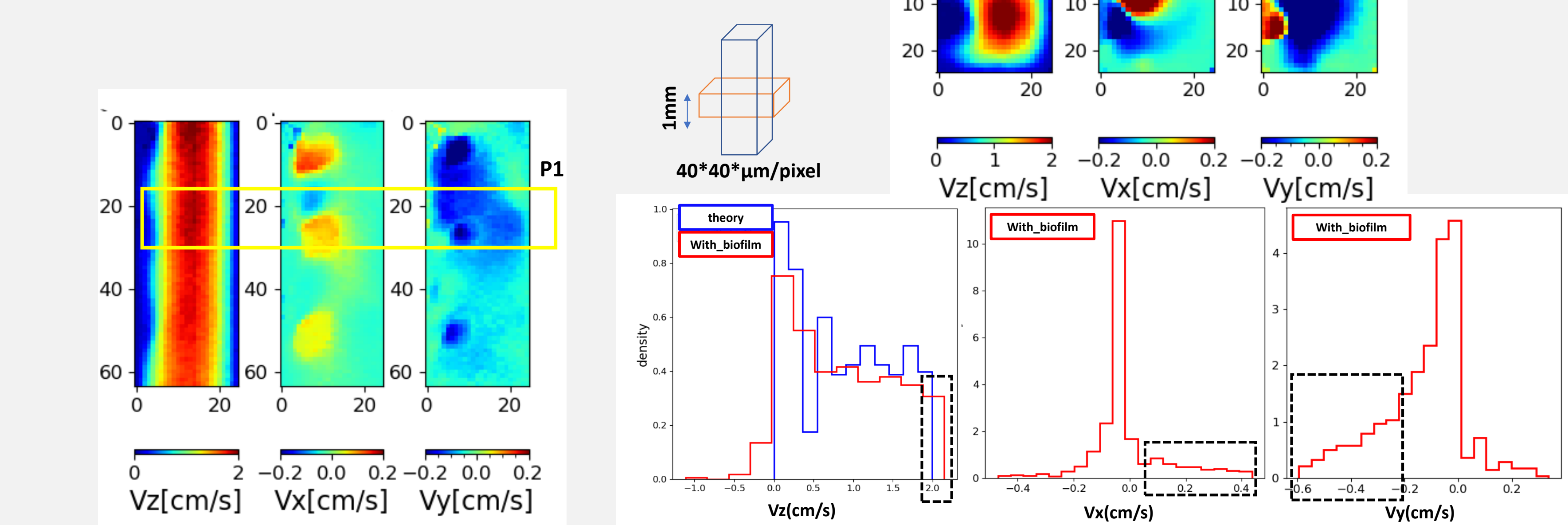
#### Longitudinal relaxation measurements

Spin echo; protocol RARE VTR; TE=10ms; 10 TR [100-10000ms]; RARE Factor=2; 2 averages; experiment time 40min



#### Velocity measurements

Gradient echo; TR=1000ms; TE=7ms; experiment time 6min



- ✓ Test of a biofilm growth experiment at the pore scale
- ✓ Visualize by MRI a biofilm development and its impact on hydrodynamics

## 4. Conclusions

- We developed a MRI instrumentation and implemented milli-fluidic devices with simple, fast prototypes and low-cost materials
- We improved the signal to noise ratio by the development of RF milli-coils
- These methods perform precise measurements of milli-fluidic phenomena which allows the inspection of complex systems

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