ETH zürich

Fluidized Beds with Internals: Real-Time Magnetic Resonance Imaging of Gas Bubbles and Particle Motion

Alexander Penn[1,2], Christopher M. Boyce[1,3], Nicholas Conzelmann[1], Klaas P. Pruessmann[2] and Christoph R. Müller[1]

[1]Department of Mechanical and Process Engineering, ETH Zurich

[2]Institute for Biomedical Engineering, University of Zurich and ETH Zurich

[3]Department of Chemical Engineering, Columbia University

The challenge to «look» inside granular systems

Tomographic techniques are required to image interior of 3D systems:

- X-ray CT [1]
- Electrical capacitance tomography [2]

Can measure particle position only

- Magnetic resonance imaging (MRI) [3,4]

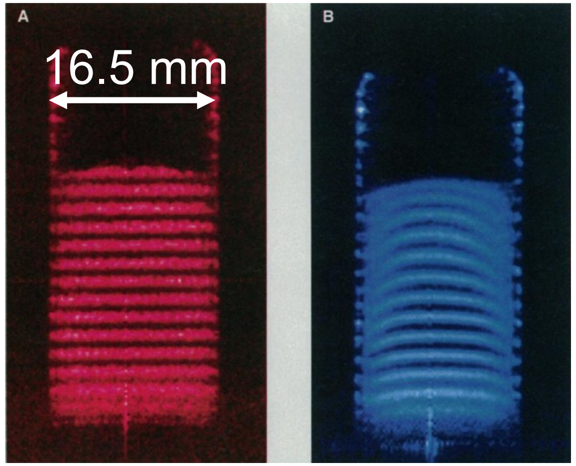
Can measure particle position, motion, acceleration, diffusion, force chains, temperature and chemical reactions

Professor Martin Rhodes at Monash University, Melbourne, Australia

[1] Mudde, R. F., *Ind. Eng. Chem. Res.* **49,** 5061–5065 (2010)
[2] Chandrasekera et al., *Chem. Eng. Sci.* **126**, 679–687 (2015)
[3] Ehrichs et al., *Science* **267**, 1632–1634 (1995)
[4] Mueth et al., *Nature* **406**, 385–389 (2000).

Previous works on MRI of granular dynamics

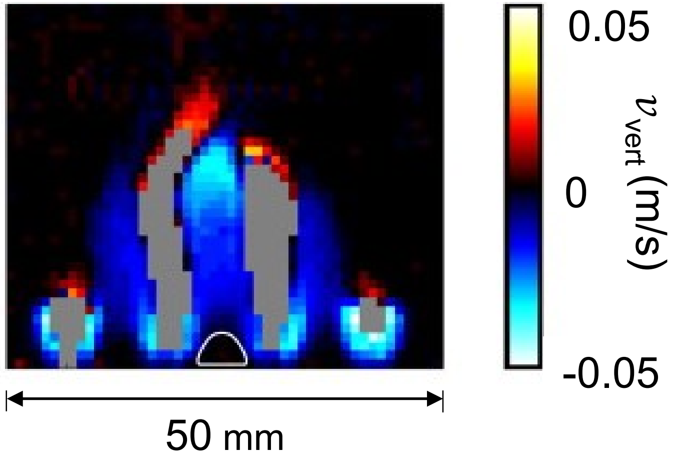
MR tagging velocimetry



Ehrichs et al., *Science* **267**, 1632–1634 (1995)

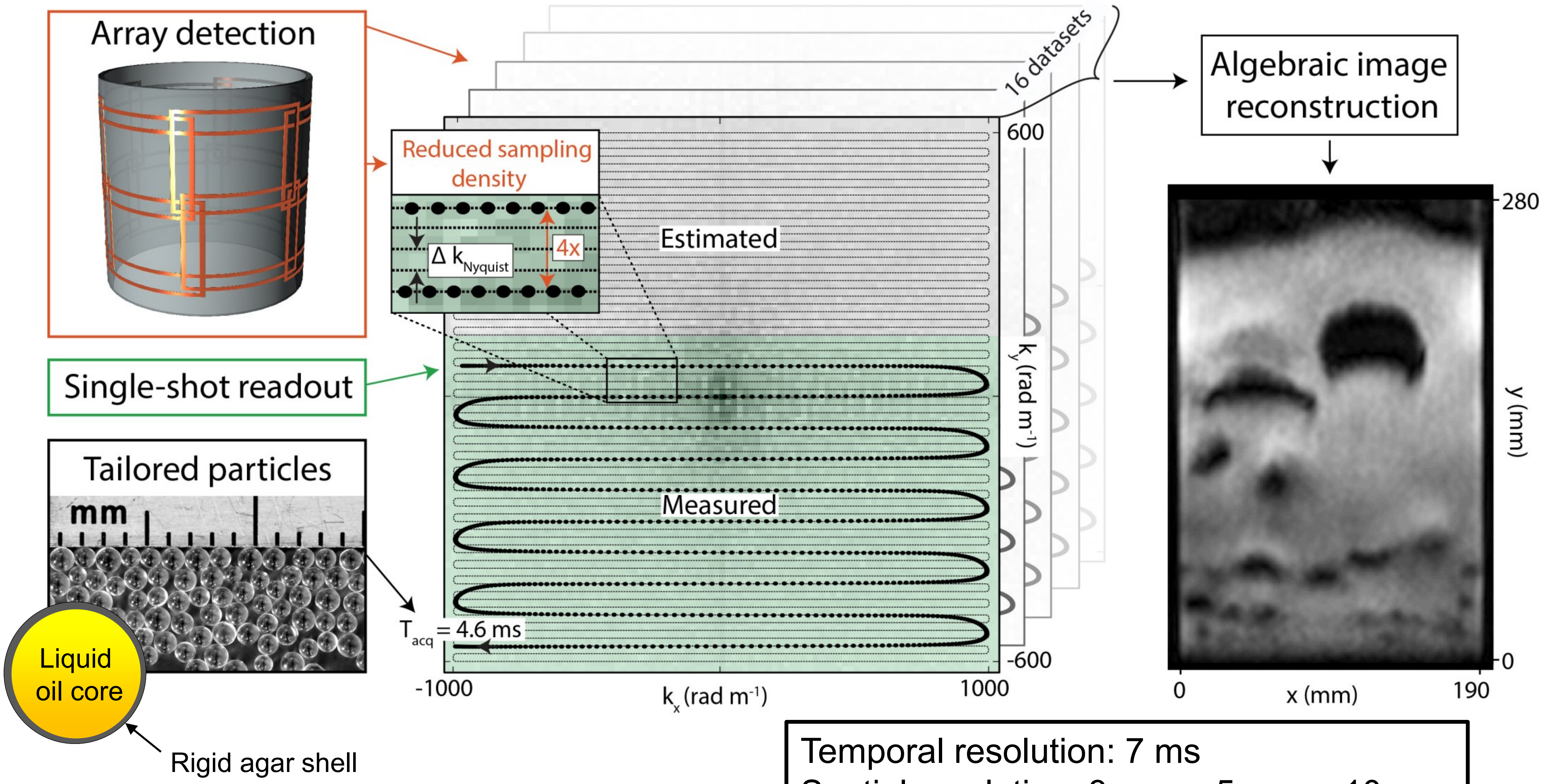
Poor temporal resolution
&
Small system sizes

Phase contrast velocimetry



Pore *et al.*, *Particuology*, **10,** 2, 2012

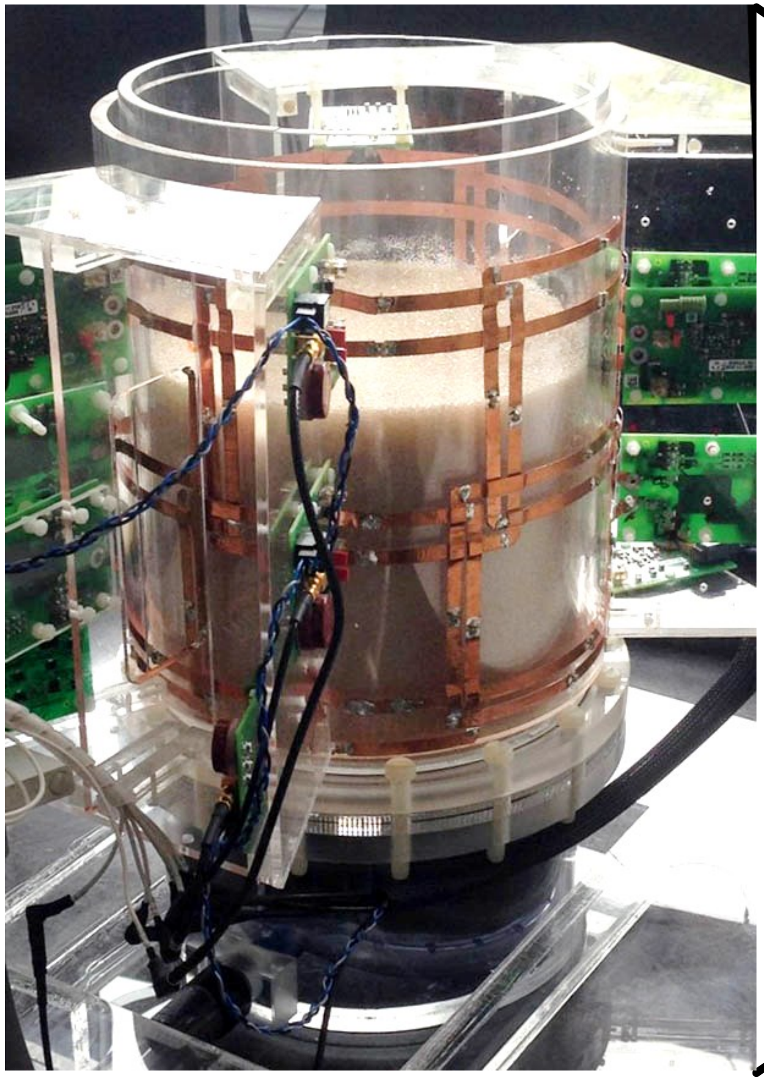
3. Enabling real-time MRI of granular dynamics



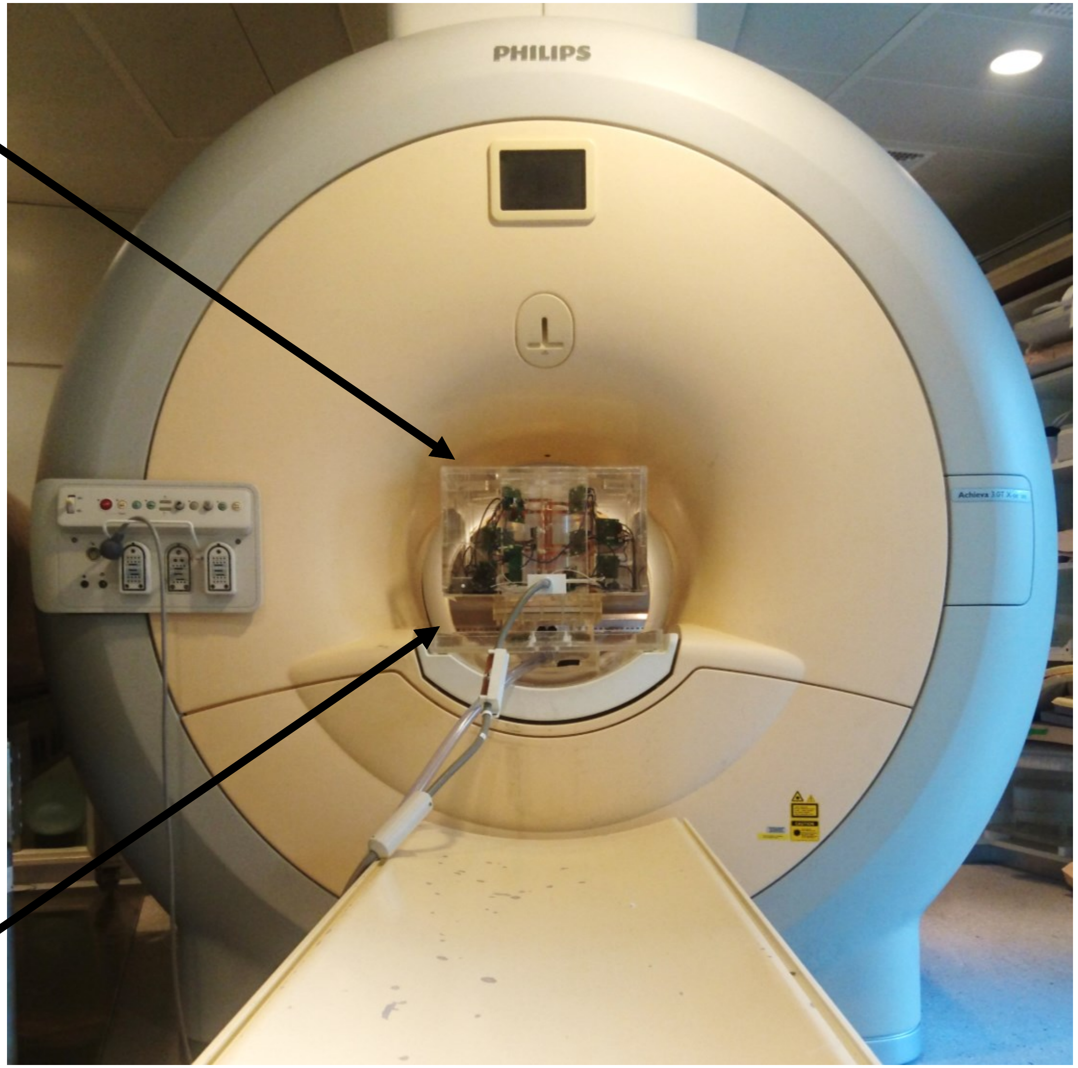
Temporal resolution: 7 ms
Spatial resolution: 3 mm × 5 mm × 10 mm

Penn et al., *Science Advances*, **3**(9), *2017*

Experimental fluidized bed setup

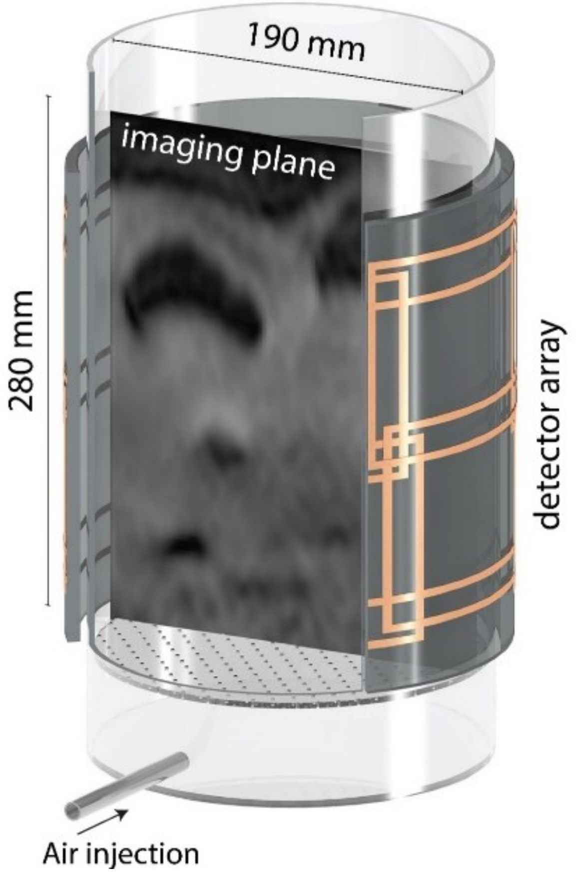


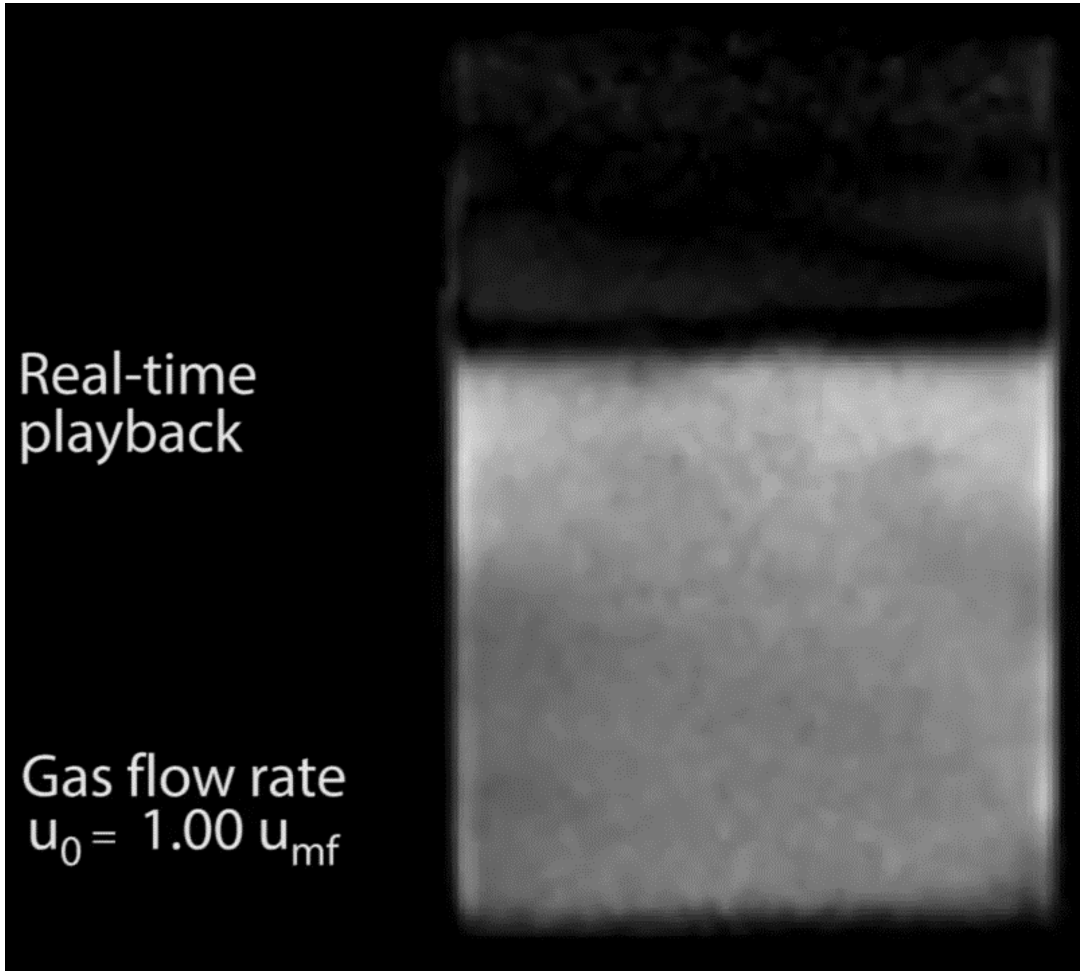
3T full body MRI scanner at ETH Zurich



Real-time MRI of bubbling fluidized beds

$u_0 = 1.2\ u_{mf}$



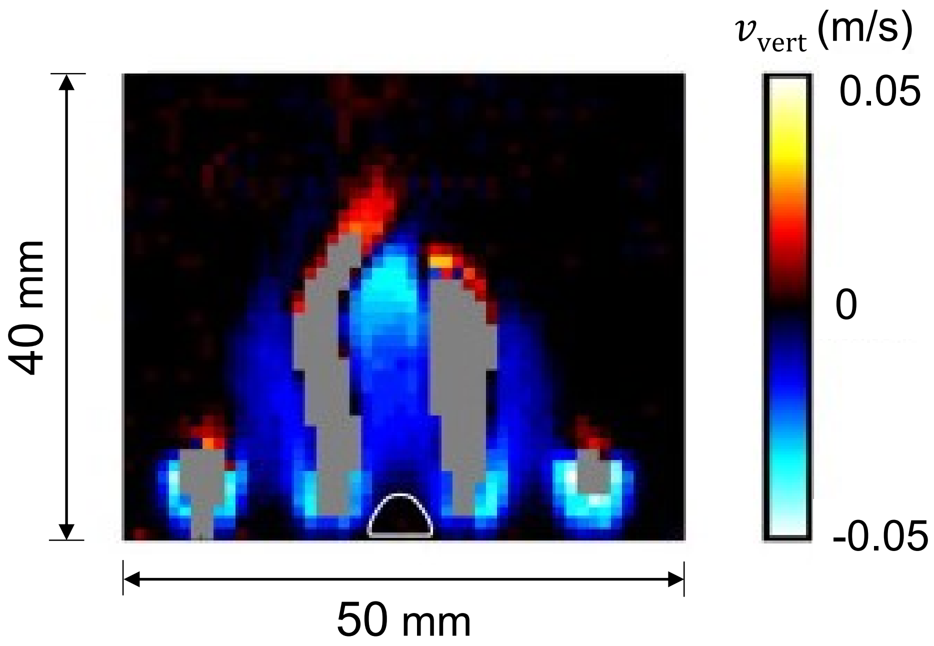


MRI velocimetry: Advancement in temporal resolution

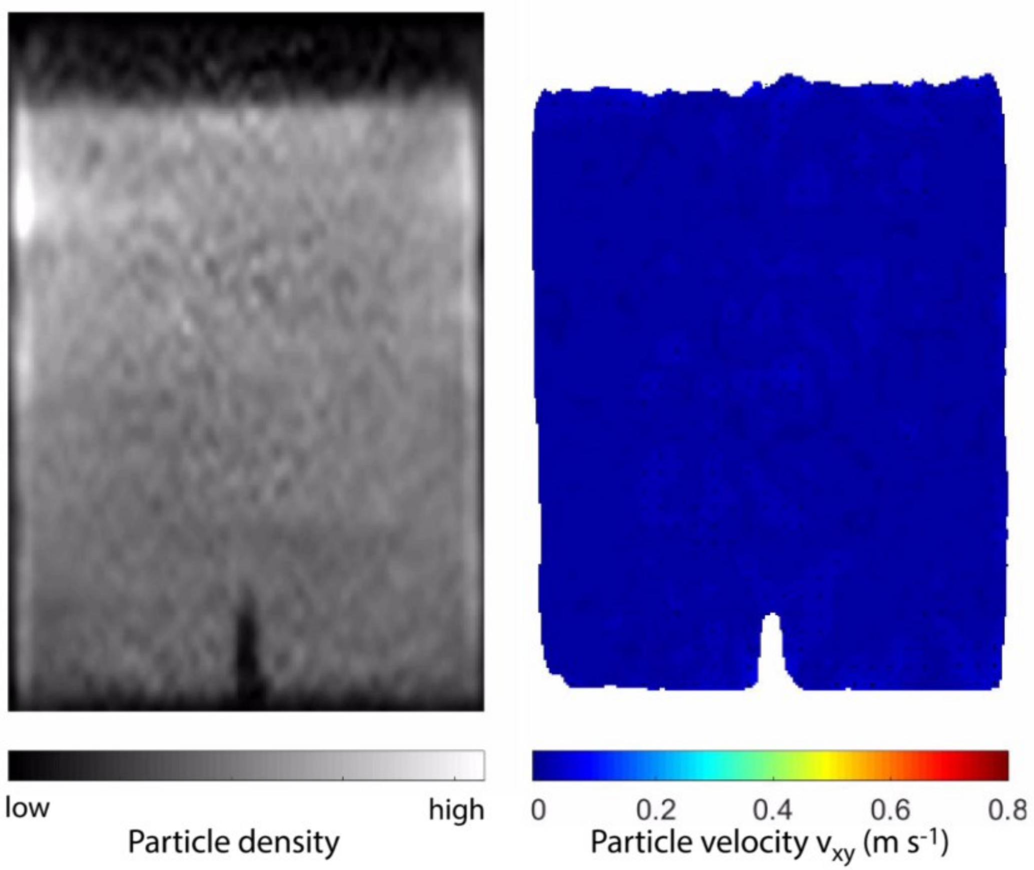
Previous work:
Temporal resolution: **20 min**

> 10^4 x faster

This work:
Temporal resolution: **24 ms**

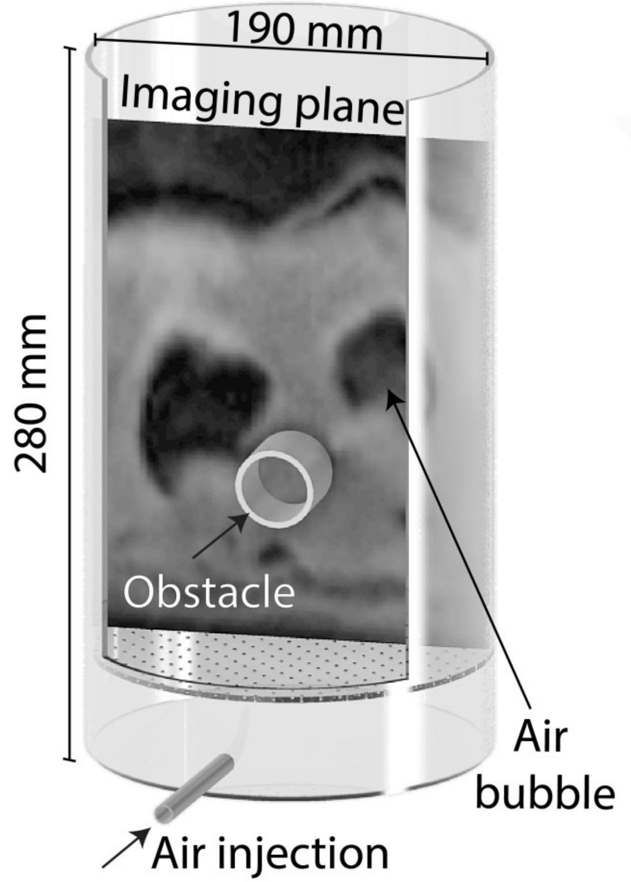


Pore *et al.*, *Particuology*, **10**, 161, 2012

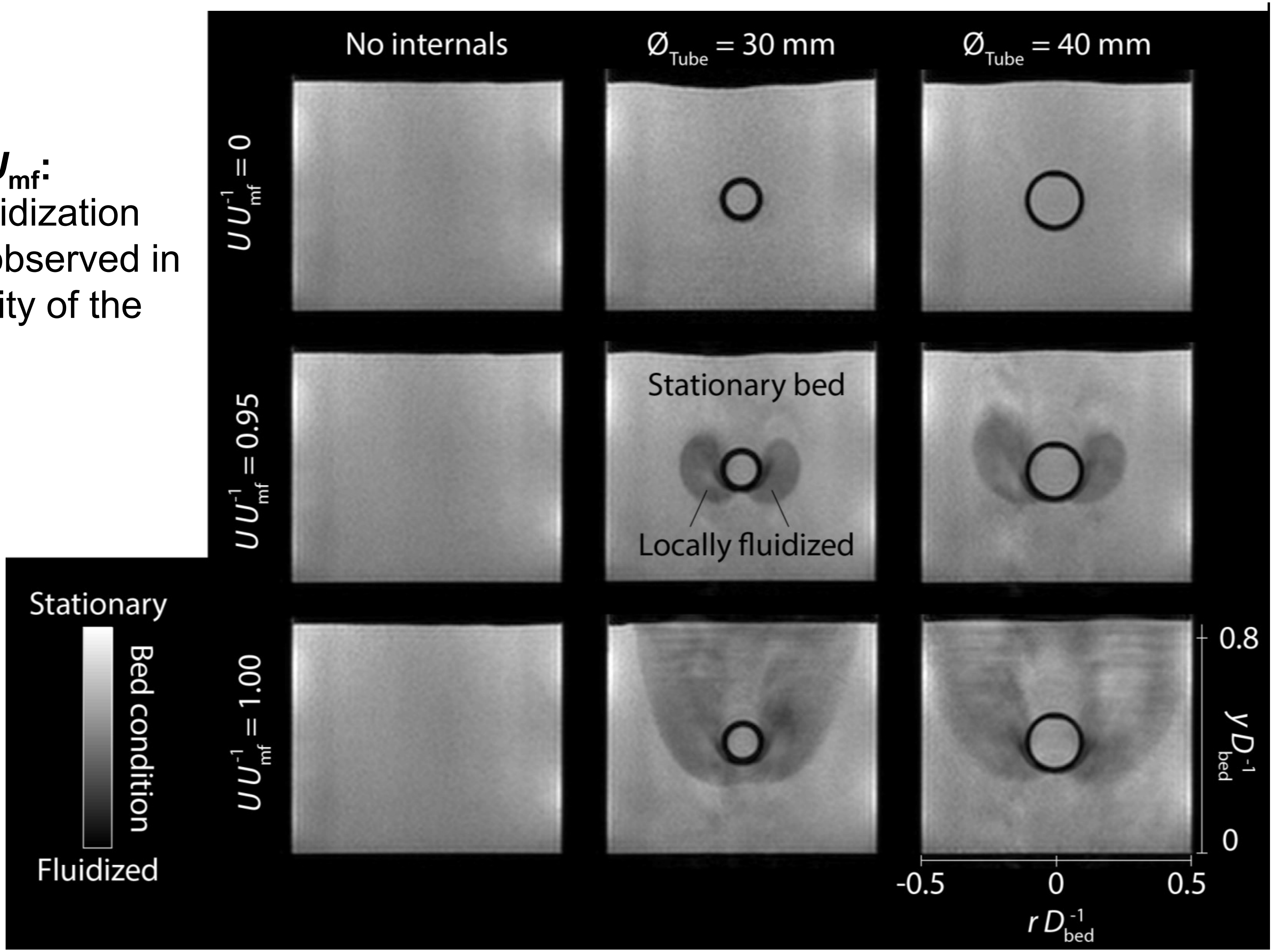


Penn et al., Sci. Adv. **3**, (9) *e1701879, 2017*

Fluidization hydrodynamics in beds with a cylindrical obstacle



Below U_{mf}:
Local fluidization can be observed in the vicinity of the obstacle

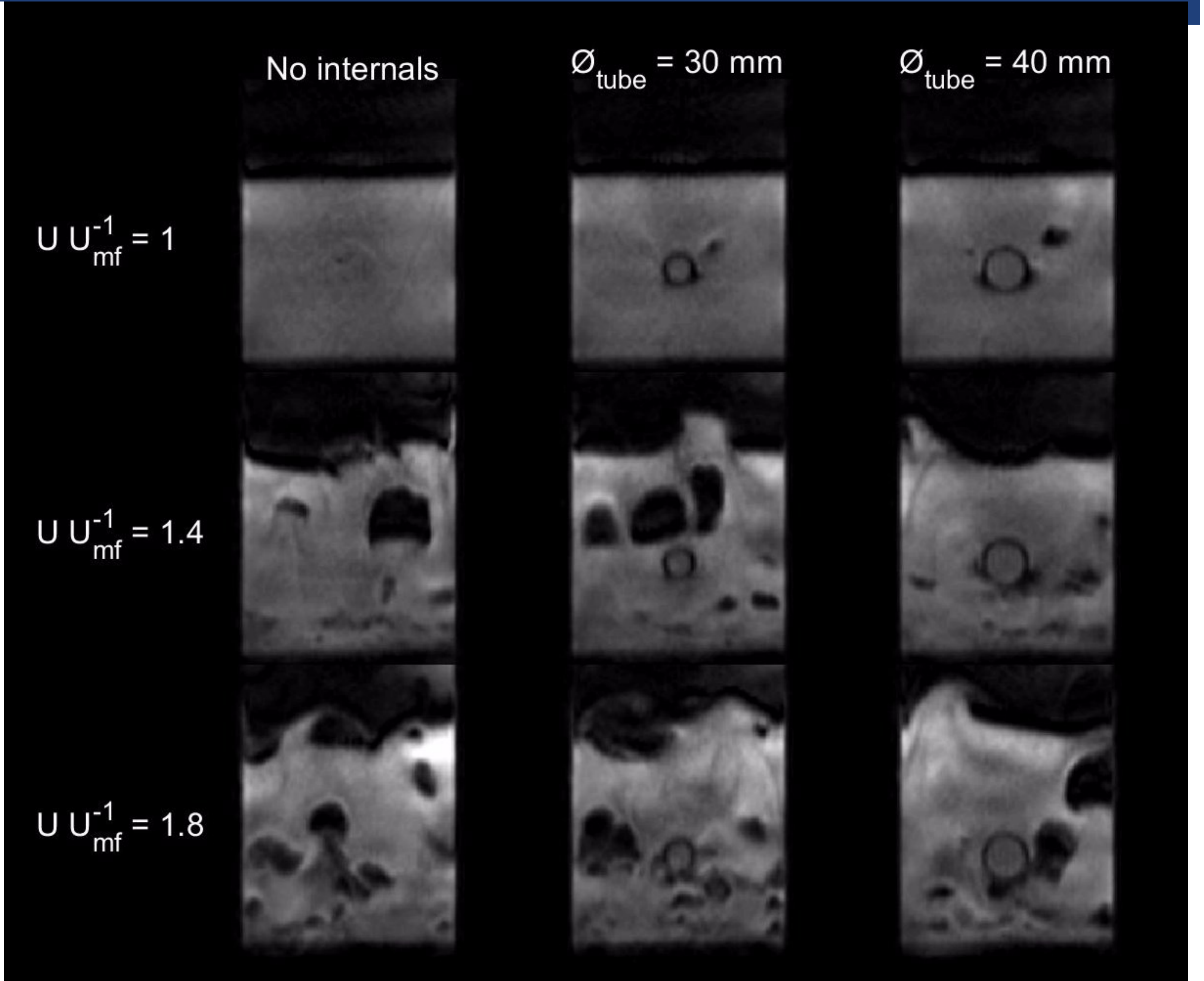


Penn et al., *Chem. Eng. Sci.*,198 (2019)

Bubble dynamics

Local concentration of gas flow around the internal causes bubbles to form to the side of the internal at $U = U_{mf}$ (top row)

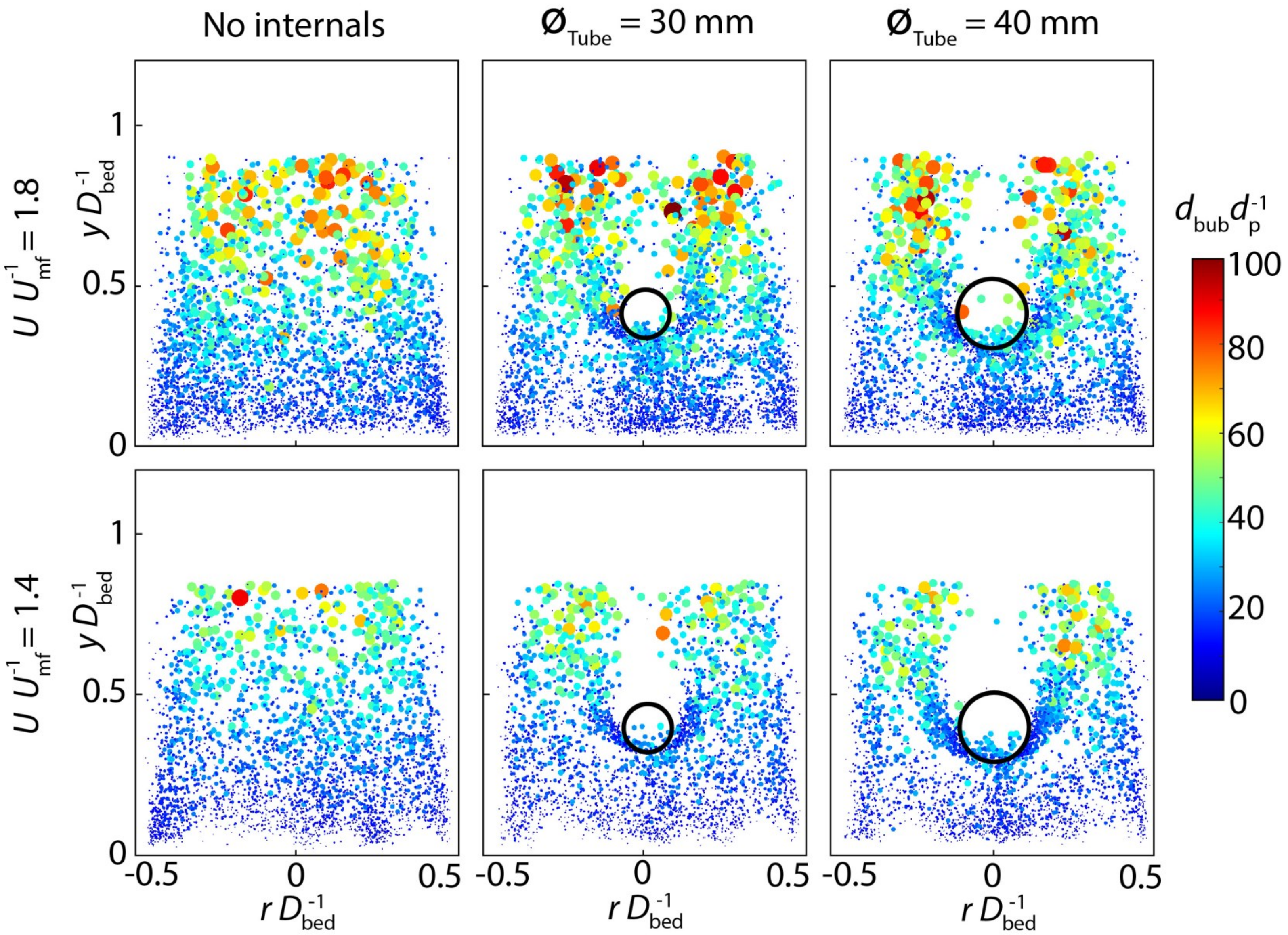
At higher gas flow rates ($U > U_{mf}$) bubbles are observed throughout the bed.



Penn et al., *Chem. Eng. Sci.*,198 (2019)

Spatial distribution of gas bubbles in the bed

- Color and size of dots indicate the size of gas bubbles
- Gas bubbles are deviated by the obstacles
- The wake region of the obstacle shows a strongly reduced number of bubbles.

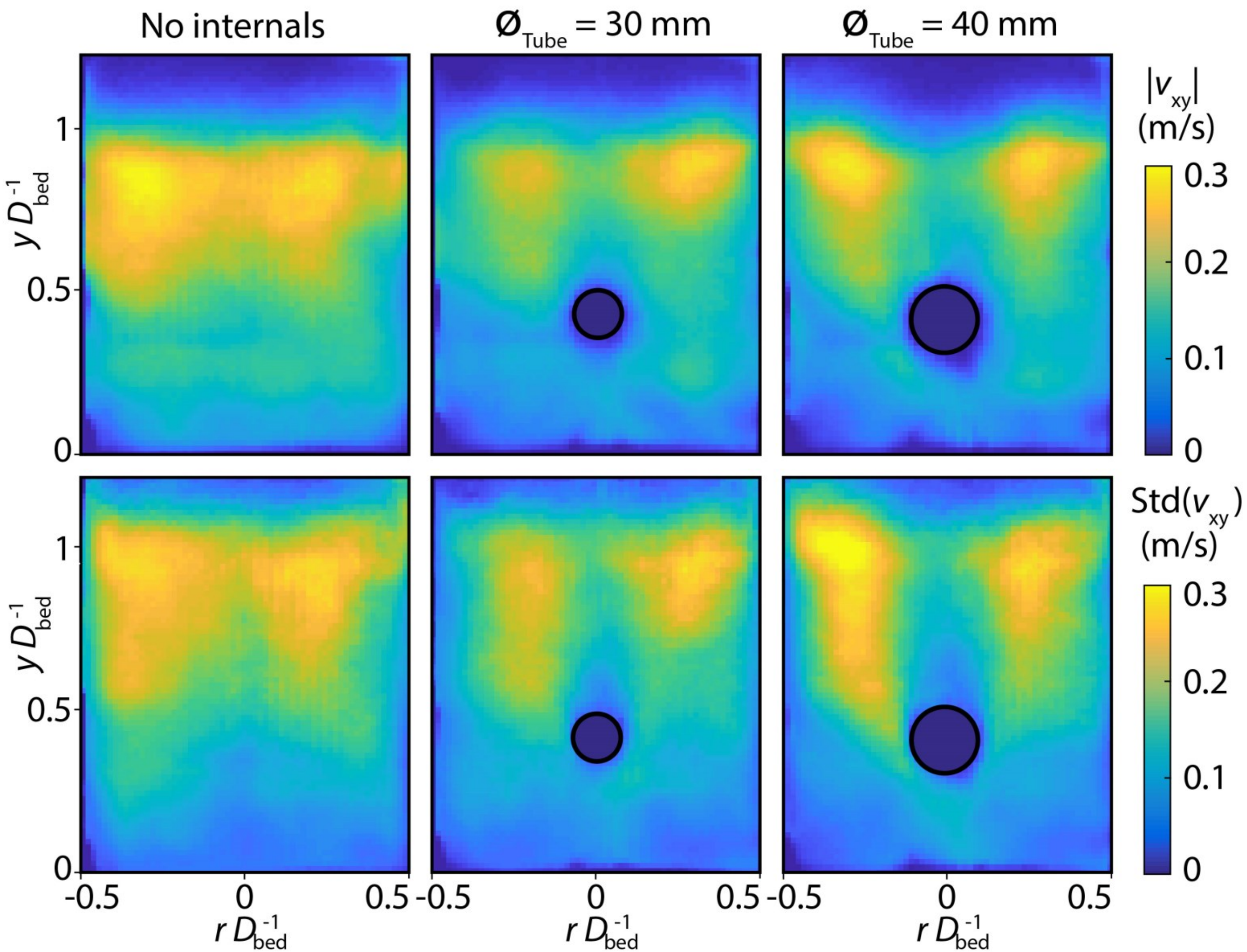


Penn et al., *Chem. Eng. Sci.,*198 (2019)

Particle velocity distribution in the bed

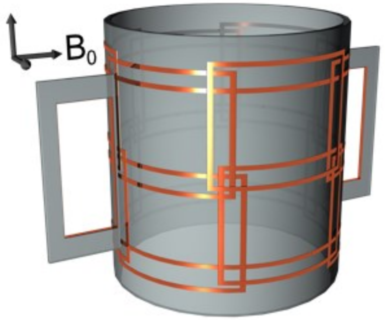
In-plane particle velocity (time-averaged)

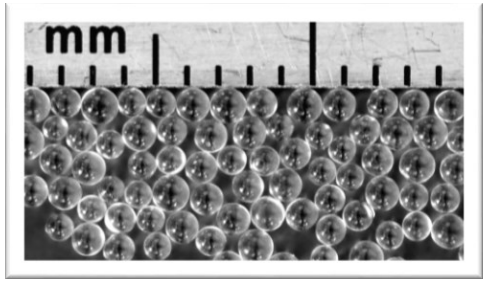
In-plane velocity fluctuations

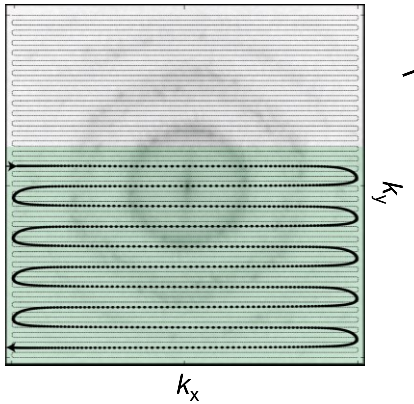


Penn et al., *Chem. Eng. Sci.*,198 (2019)

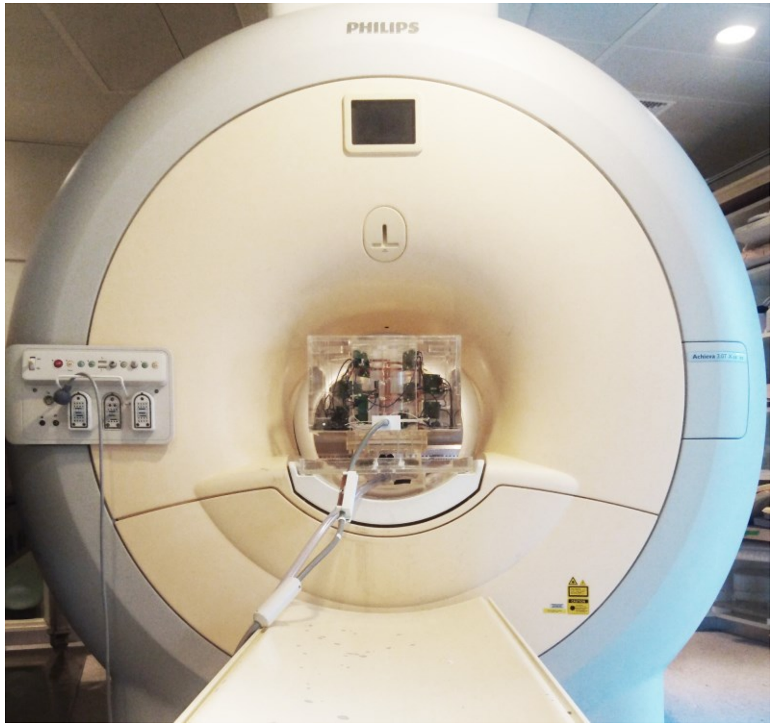
Summary







MRI now allows to study 3D granular dynamics in real-time



Penn et al., *Science Advances,* 3(9), (2017)