Real-time imaging of granular dynamics

Alexander Penn[1,2], *Christopher M. Boyce*[2,3], *Klaas P. Pruessmann*[1], *Christoph R. Müller*[2]
[1]Institute of Biomedical Engineering, ETH Zurich and University of Zurich, Zurich, Switzerland
[2]Department of Mechanical and Process Engineering, ETH Zurich, Zurich, Switzerland
[3]Department of Chemical Engineering, Columbia University, New York, NY, USA

The dynamics of granular materials govern natural phenomena ranging from earthquakes, to avalanches to landslides and are critical for a variety of industrial applications. Our fundamental physical understanding of granular dynamics, however, is still incomplete. One major challenge towards a better understanding of granular dynamics is the difficulty to obtain spatially and temporally resolved measurements of particle dynamics from the interior of 3D granular systems. Magnetic resonance imaging (MRI) is able to measure a variety of relevant system properties, however, one of the largest limitation so far has been the rather low temporal resolution. Here we report our recent developments, an MRI methodology that increases the temporal resolution of phase contrast velocity encoded imaging of granular dynamics by more than four orders of magnitude, effectively advancing MRI of granular dynamics from temporally averaged to real-time imaging [1]. The advances are enabled by an interplay of engineered MR signal sources, time-efficient single shot readouts and radiofrequency (RF) hardware developments and provide insight into hitherto unknown facets of dynamic granular behavior (Fig.1). We are confident that the methodology will be useful for studying a variety of dynamic granular systems in the fields of process engineering, granular physics and geophysics.

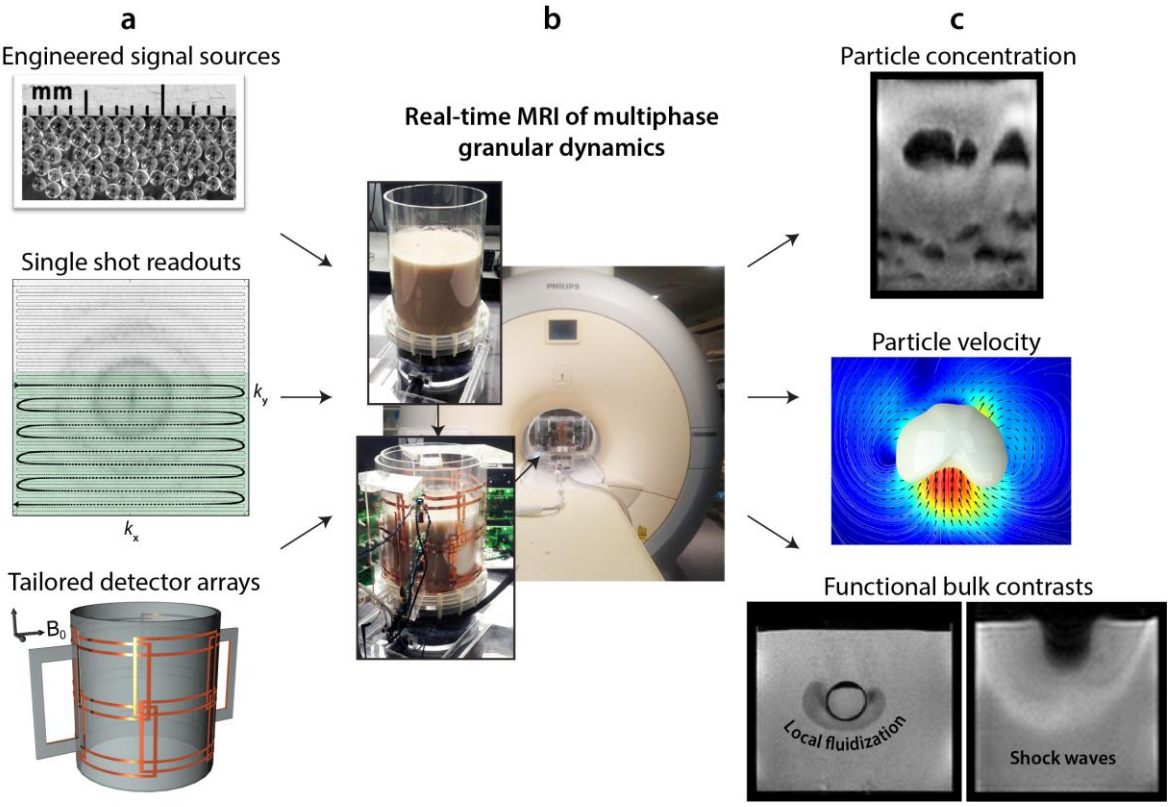

Figure 1. (a) Real-time MRI of granular dynamics is enabled by a concerted interplay of granular signal source engineering, time-efficient single-shot pulse sequence design and array detection using custom-build RF detector arrays. (**b**) A fluidized bed model system (diameter 190 mm) was placed inside the RF detector array and inserted into the bore. (**c**) The methodology has been used to acquire instantaneous snapshots of local particle concentration and particle speed. Moreover, it was used to produce MR contrast based on fluidization and shock waves in granular materials.

References:

[1] A. Penn, T. Tsuji, D. O. Brunner, C. M. Boyce, K. P. Pruessmann, and C. R. Müller, Sci. Adv. **3**, e1701879 (2017).