New Horizons for Optimization in Fluid Mechanics

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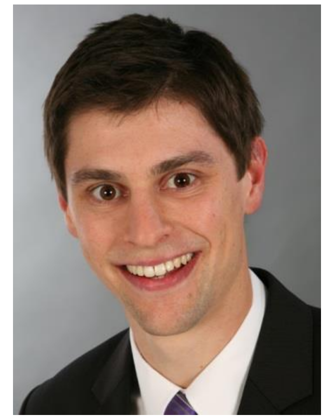
Personnel



Felix Loosmann

- PhD student
- Graduate School of Computational Engineering
- Enhanced compact heat exchangers

Florian Wassermann

- PhD student
- Center of Smart Interfaces
- Magnetic Resonance Thermometry

Cooperative Research

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UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE & ENGINEERING
Centre for Advanced Coating Technologies

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SLA
Fluid Mechanics and Aerodynamics

Vision

Rapid-Prototyping offers unlimited degrees of freedom in design and manufacturing of complex components.

This introduces new challenges for the mechanical engineer, perhaps surpassing his formal education in the areas of optimization

A vision of new possibilities can be illustrated using the field of internal heat exchangers.

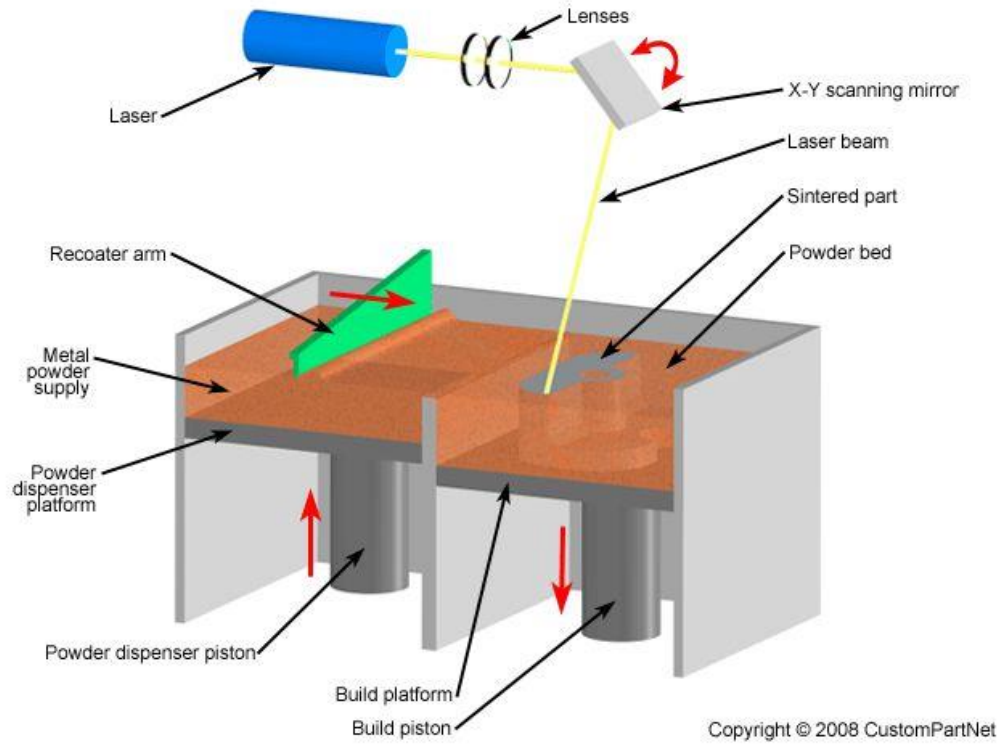
General Design Objectives

Minimize both size of the heat exchanger and the work required to pump fluid through it

Direct Laser Sintering Technology

- Manufacture 3D objects in single step directly from CAD
- No bonding issues
- Arbitrary internal structure

Optimize shape of passages for fluid flow to maximize heat transfer while reducing pressure losses

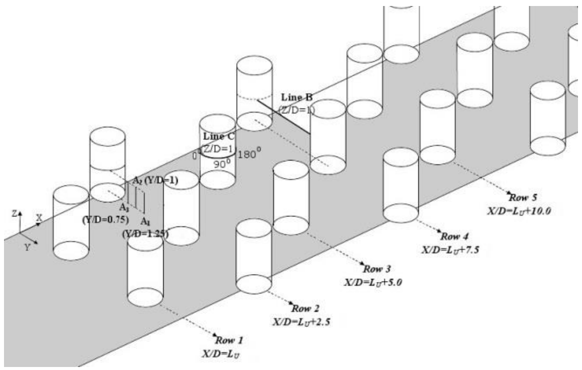


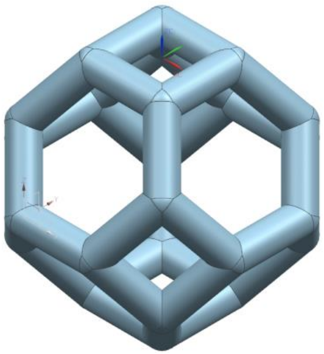
Forced convection flows in heat exchanger

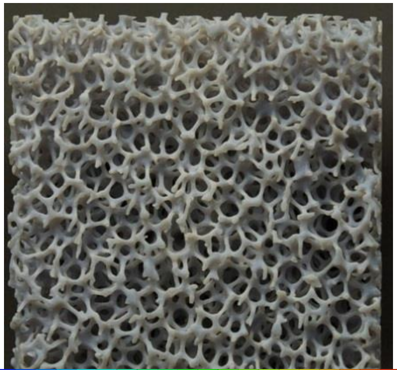
Pin Fin Array
(simple geometry)

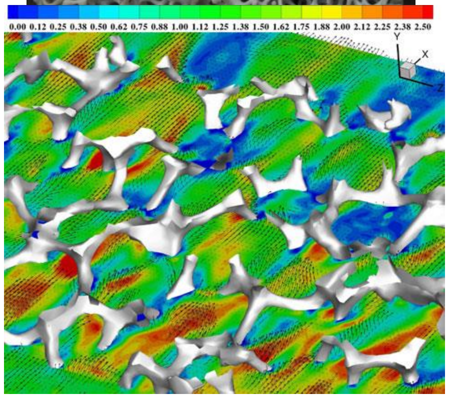
Tetadecahedron
(advanced geometry)

Stochastic Foam



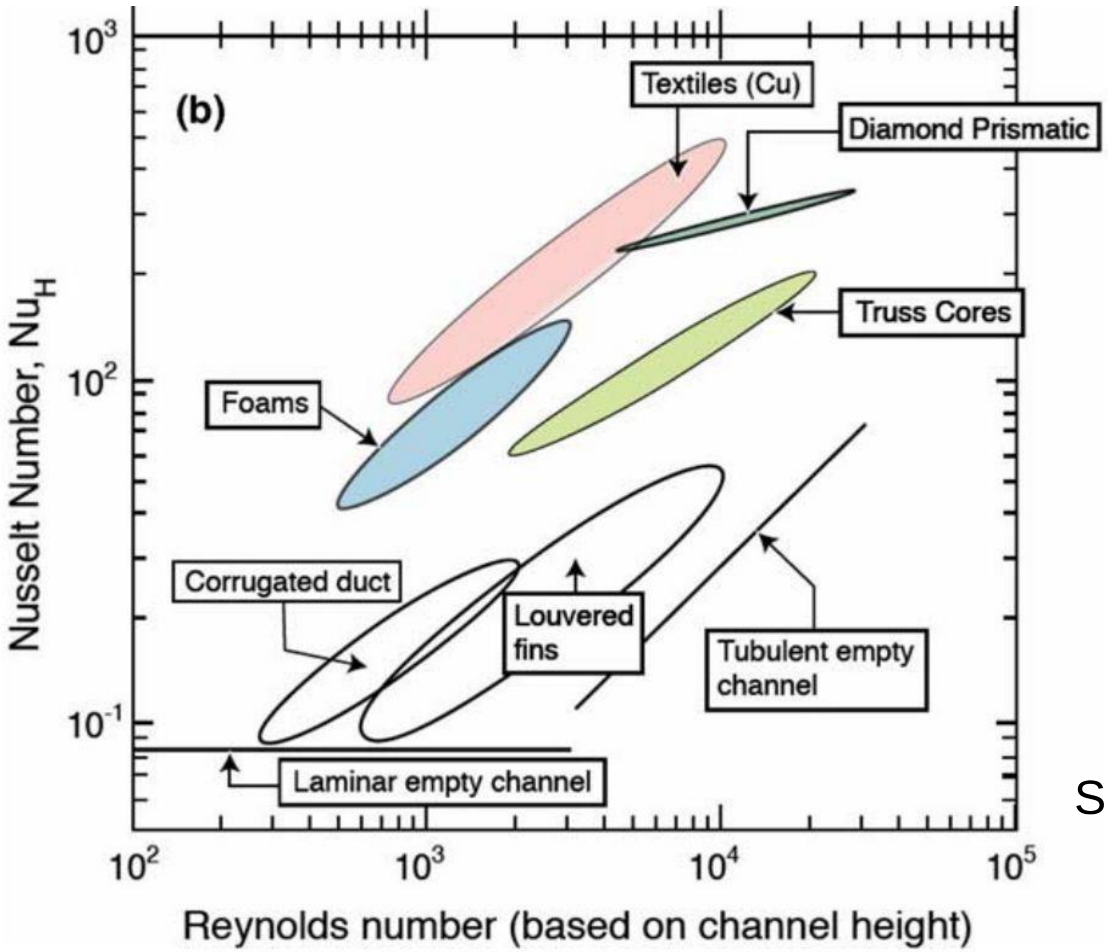






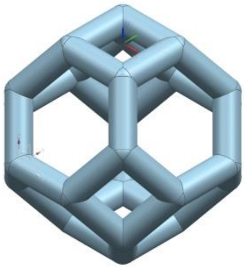
Source: Onstad et al. 2010

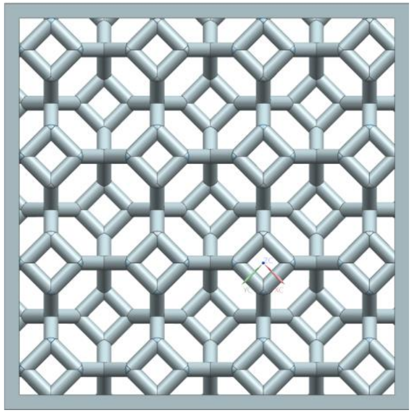
Conventional Heat Exchangers

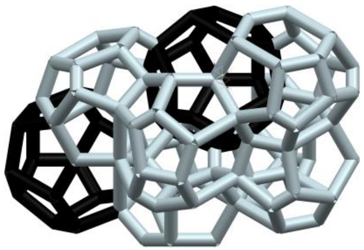


Source: T.J. Lu et al.

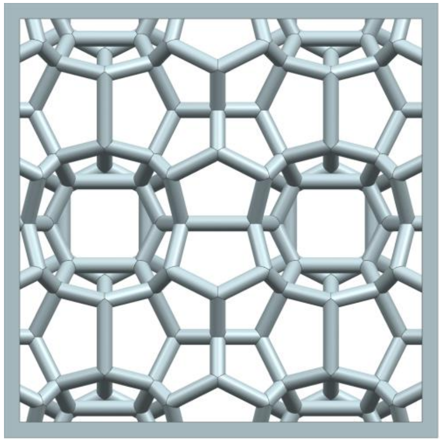
New horizons, new structures







Source: www.inhabitat.com



Tetradecahedral

- Lord Kelvin 1887
- Found in aluminium foams
- Isoperimetric quotient = 0.75

Weaire Phelan structure (1993)

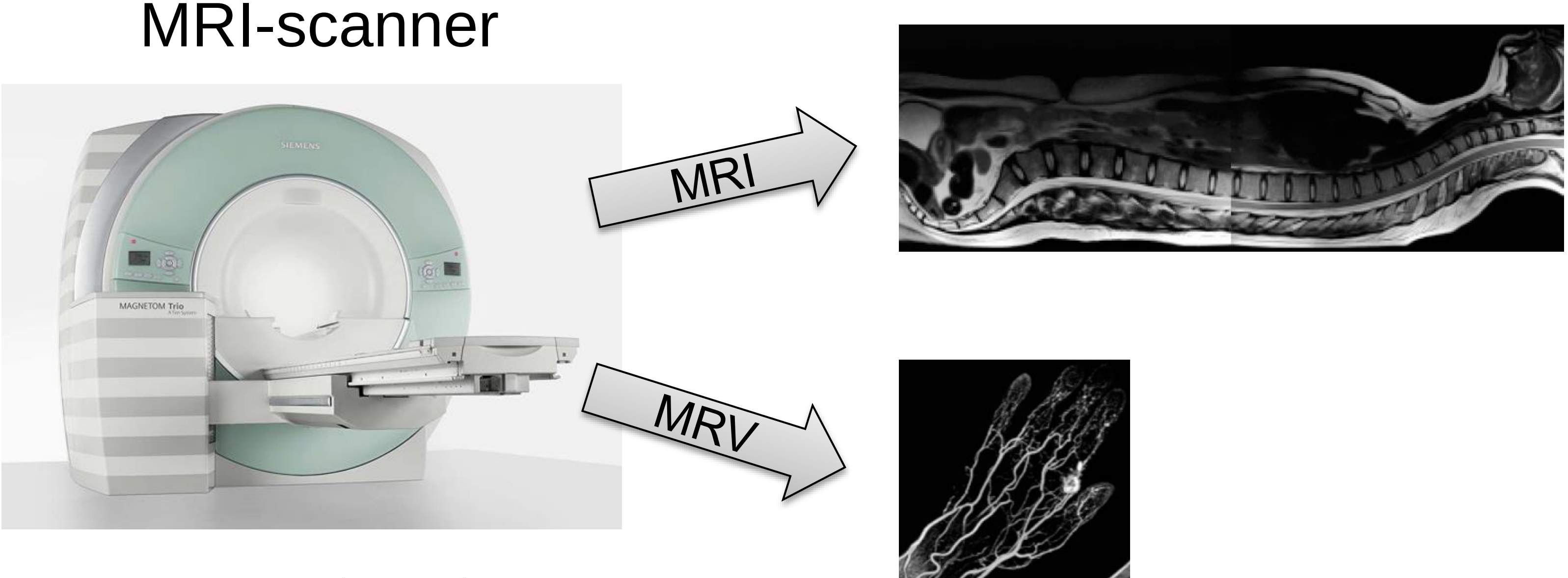
- Olympic swimming stadium in Beijing
- 8 irregular tetradecahedrons + 2 dodecahedron
- Isoperimetric quotient = 0.76

Magnetic Resonance Imaging (MRI) in Medical Applications

MRI encompasses different measurement principles

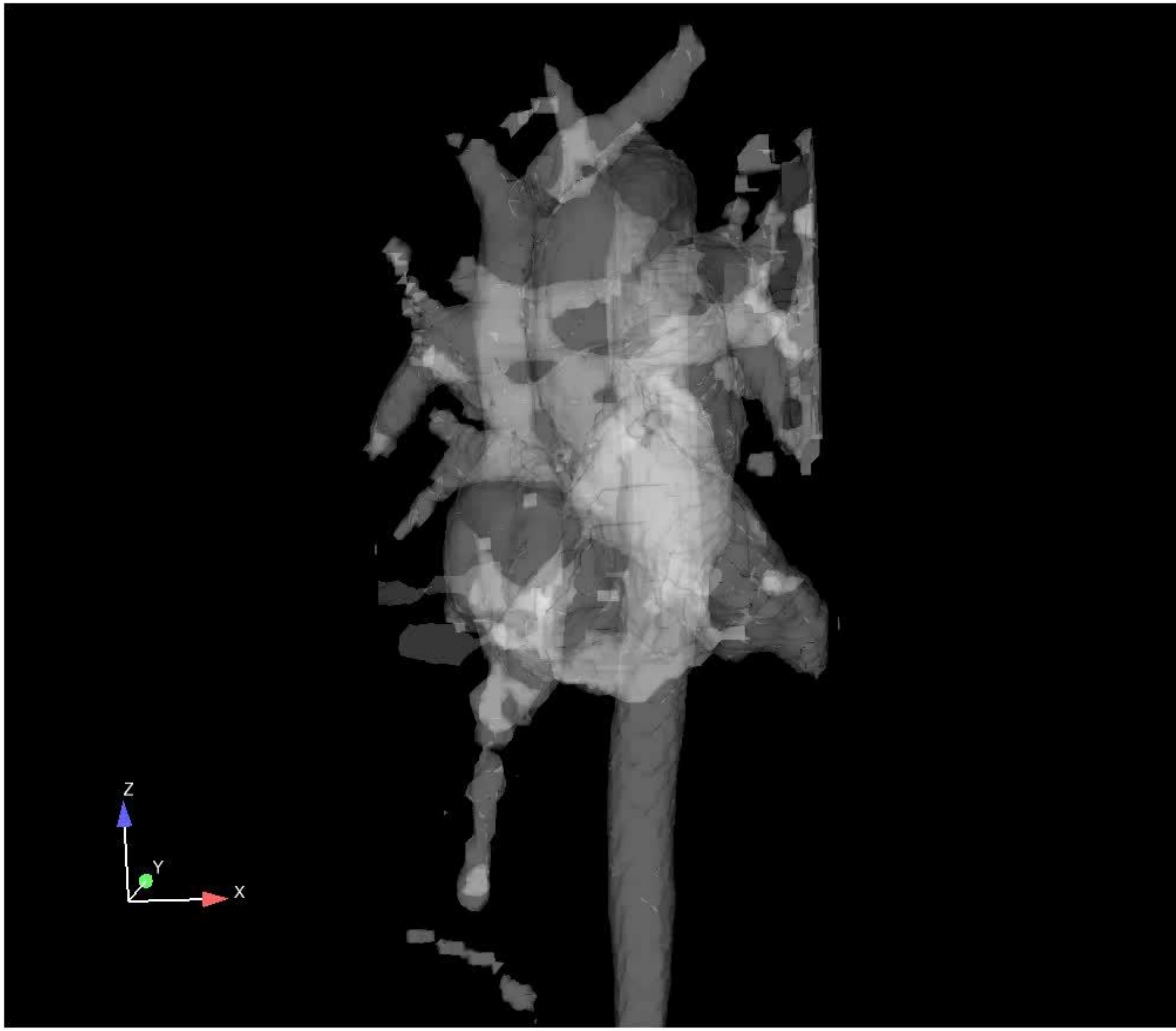
- Magnetic Resonance Imaging (MRI): visualization of tissue
- Magnetic Resonance Velocimetry (MRV): extracting fluid flow of blood vessels

MRI-scanner



Source: www.siemens.de

4D MRV by Markl et al.: A Living, Beating Heart



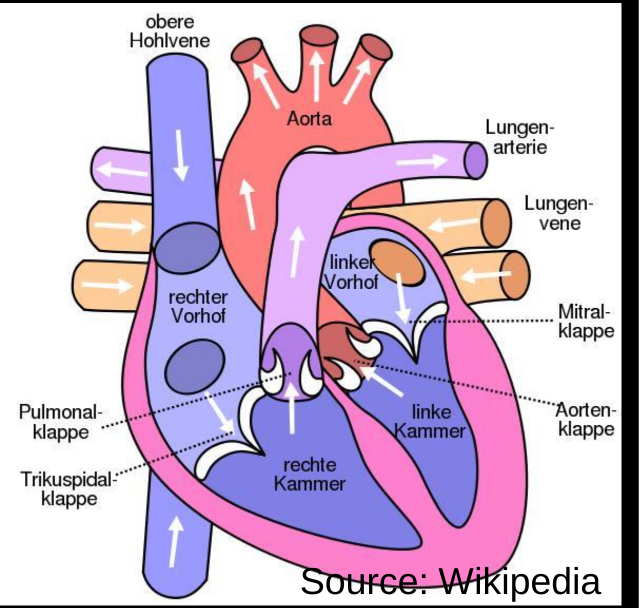
linker Herzkammer und Aorta

linke Lungenvene

rechte Lungenvene

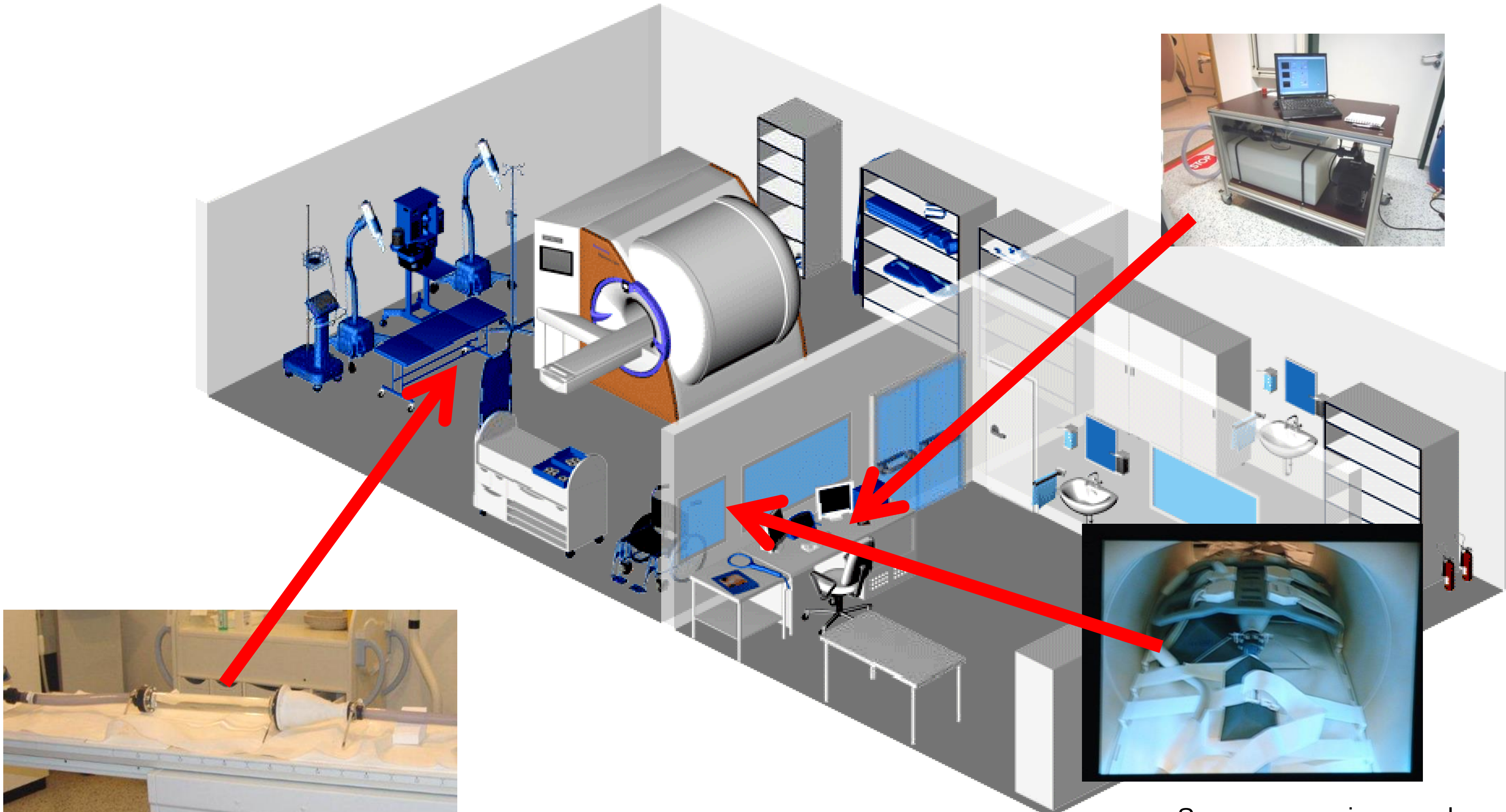
Untere Hohlvene

Obere Hohlvene



Source: Wikipedia

Magnetic Resonance Tomograph in the Clinic



Source: www.siemens.de

MRI – Possibilities and Limitations

Possibilities

- Non-invasive
- No optical access necessary
- No post-processing
- 3-dimensional data
- 3 velocity component data

Limitations

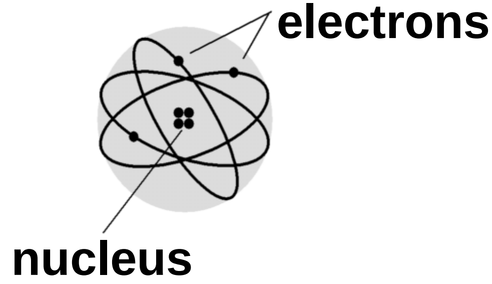
- Experiments with water flow
- No metal material
- FOV: cubical (500mm)^3
- MRV – „just“ velocities
  - Velocity range: 1cm/day up to 10 m/s
  - Steady flow
  - **But:** CineMRV, Reynolds stresses, concentration, thermometry measurements possible
- Resolution: ~0.7mm iso-volume (decreasing SNR)

Basic principle: NMR

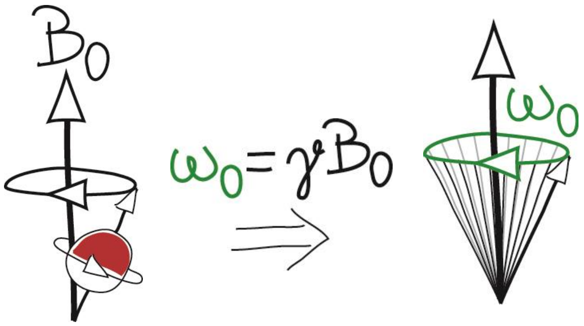
- NMR = Nuclear Magnetic Resonance
  - Using quantum mechanical features of the atomic nucleus
- Focus on Hydrogen nucleus
  - Reason: It is present in the human body!
  - 1 proton → charge
  - Spin = ½ → rotation

→“Spin Magnet”

Simple atomic model

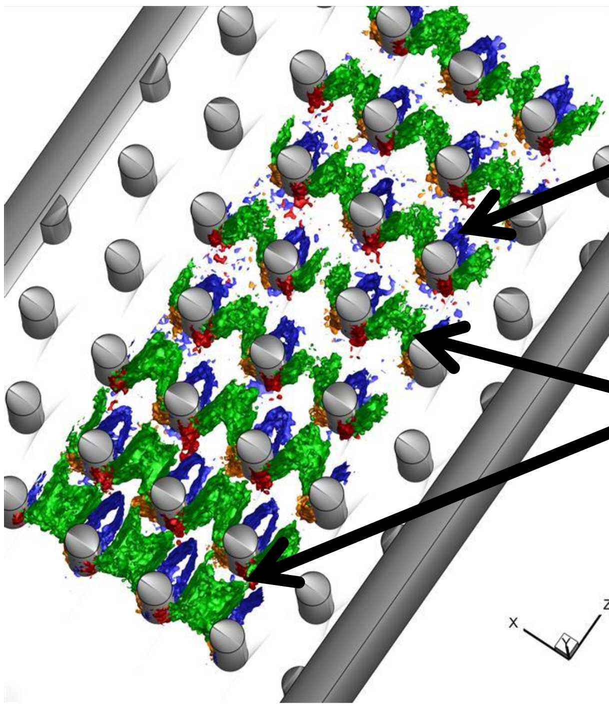


- Spin Magnet can interact with magnetic fields → measurement signal
  - Static field (B_0-field, 3 Tesla) → Spin magnet precesses
  - Dynamic fields:
    - RF pulses → stimulation
    - Gradient fields → imaging, fluid velocities



Simple Geometry: Pin Fin Array

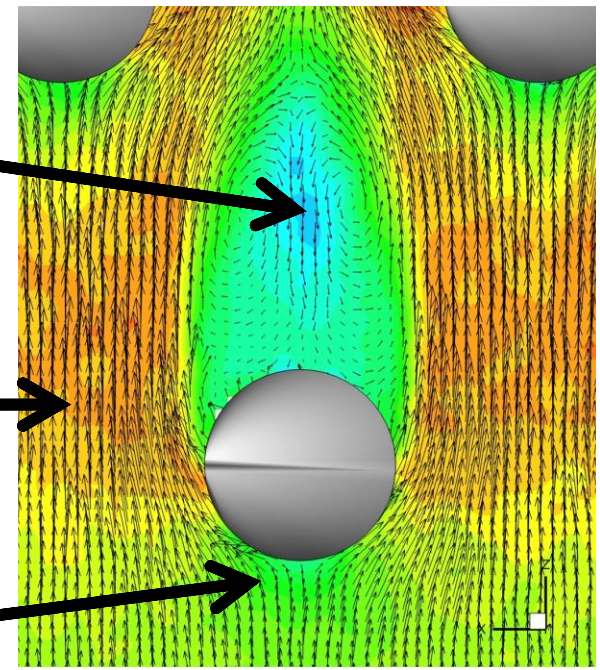
- Re=10,000
- Ercoftac SIG 15 Testcase 2



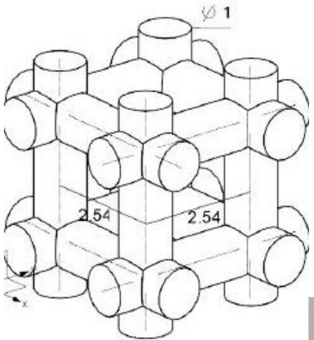
Recirculation zones,
hot spot
(blue)

High speed jets
(green)

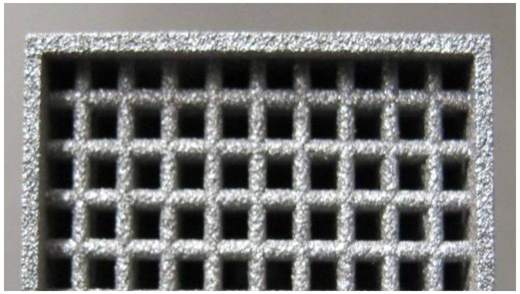
Jet impingement
→ high convective
heat transfer

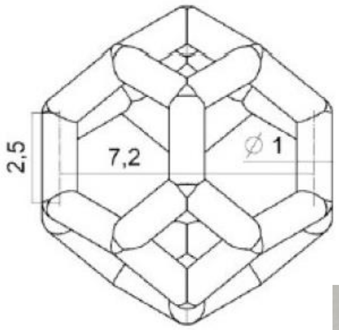


Laser Sintered Structures

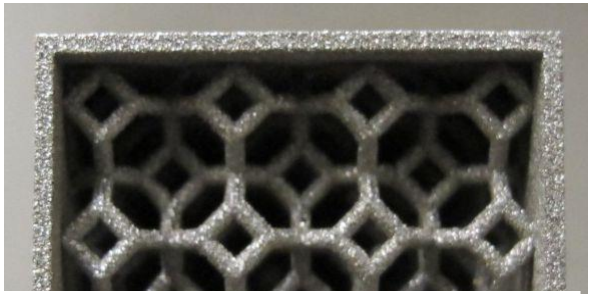


Cubic array



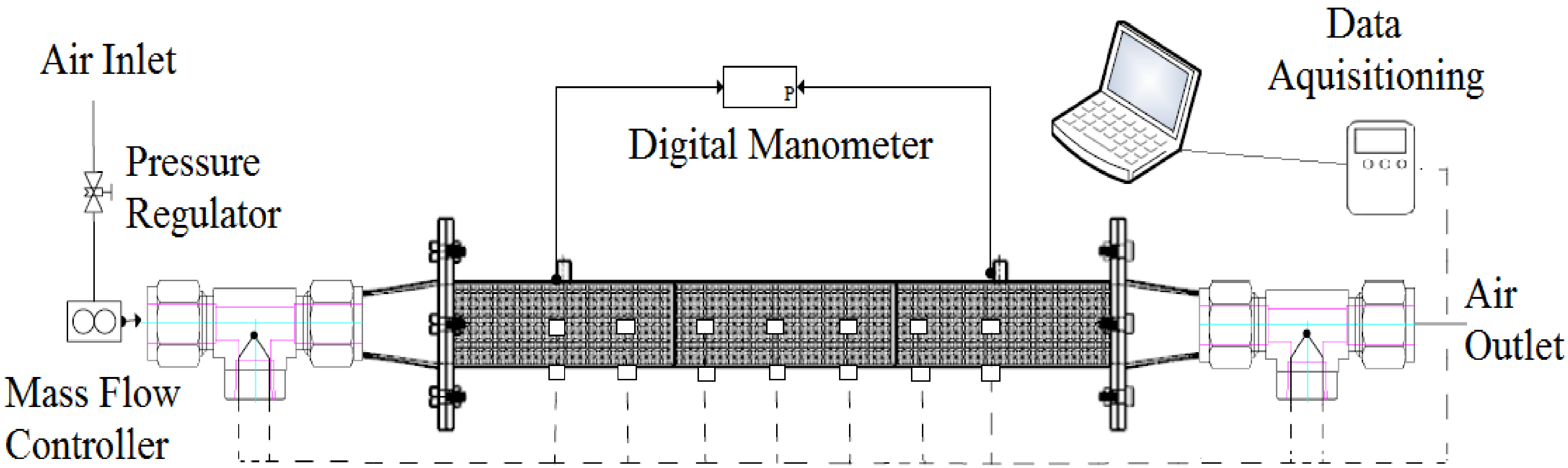


Tetradecahedral array

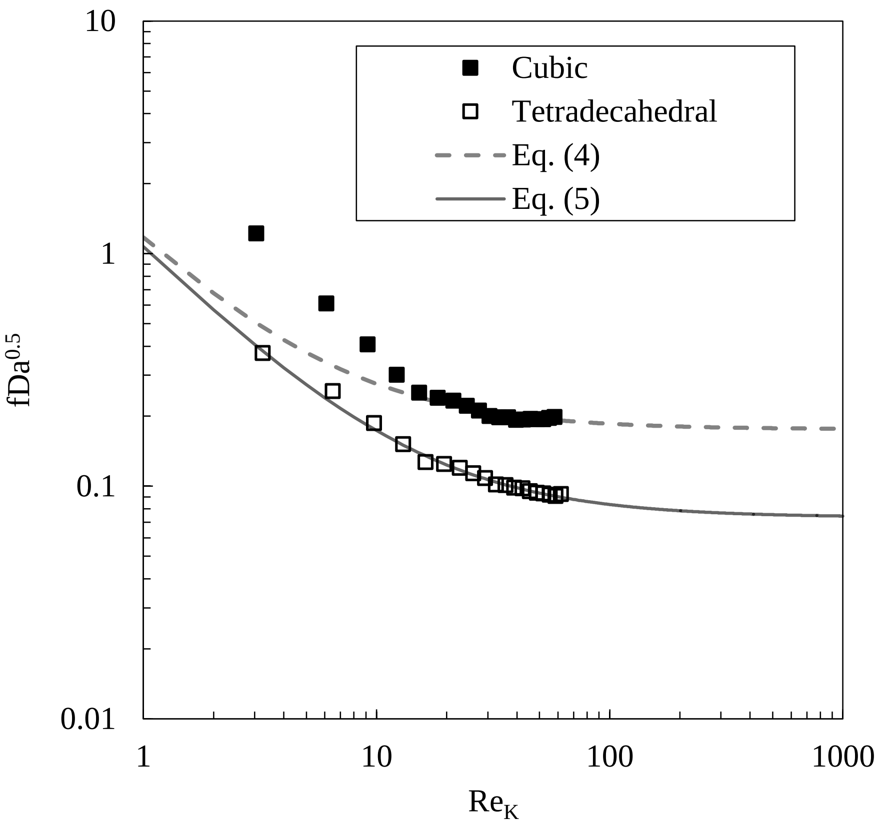


Parameter	10PPI Nickel foam	cubic	tetradecahedral	Weaire Phelan
source	Tsolas and Chandra [2010]	CAD model section	CAD model section	CAD model section
strut diameter (1e−3m)	0.331	1	1	1
pore diameter (1e−3m)	2.771	2.540	7.800	n\a
ζ (m^2/m^3)	0.407	0.890	2.074	2.550
porosity	0.940	0.750	0.894	0.923
relative density	0.060	0.250	0.106	0.077
isoperimetric quotient	n\a	0.524	0.753	0.764

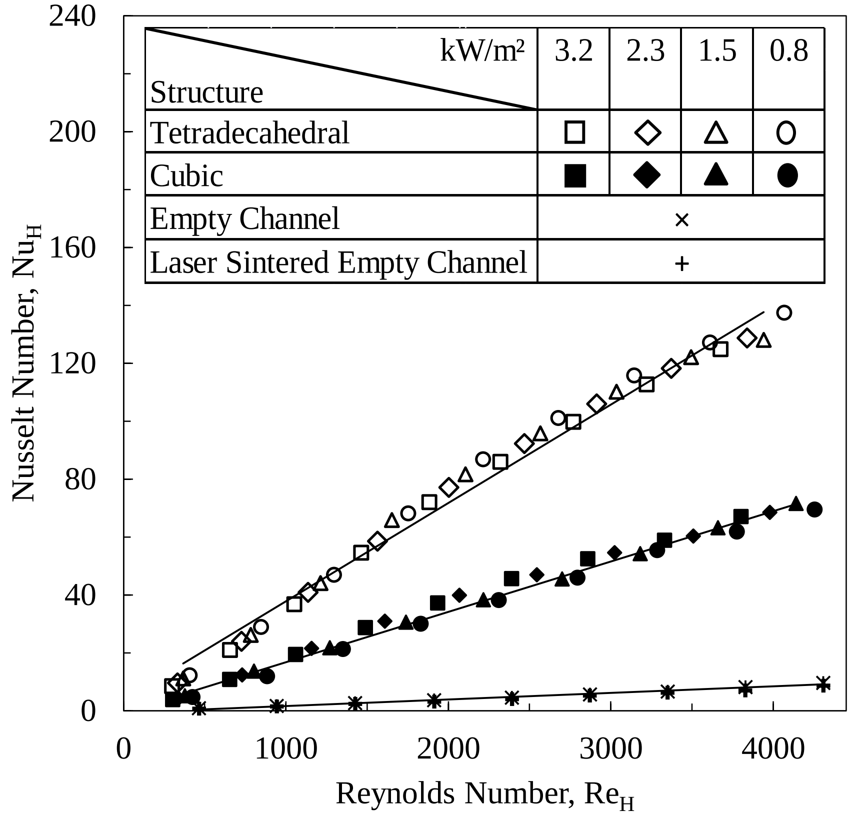
Experimental Facility (U of Toronto)



Measurement Data

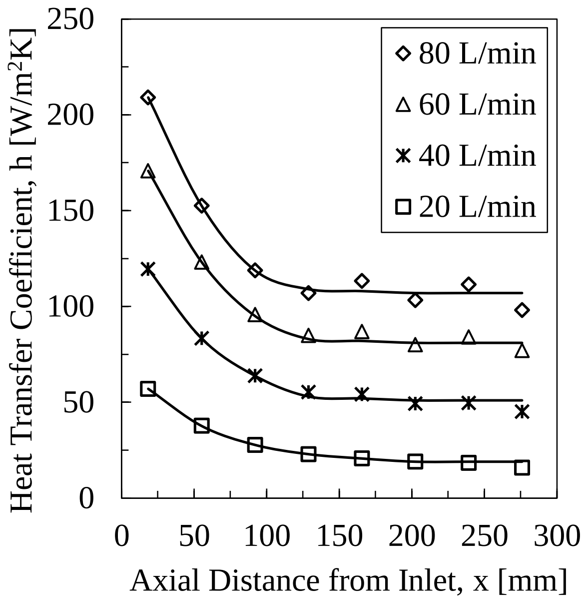


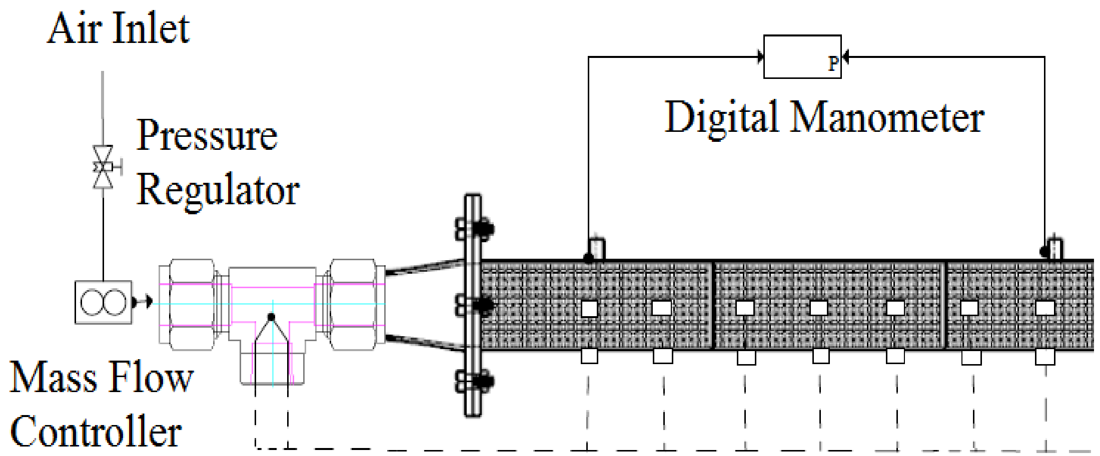
Pressure Loss



Heat Transfer

Infrared Visualization

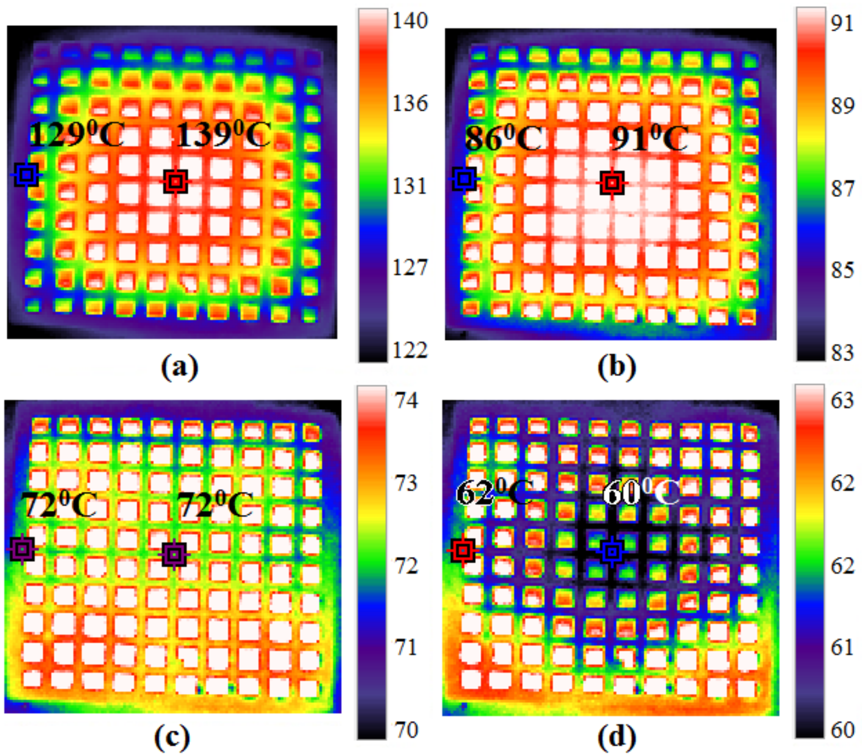




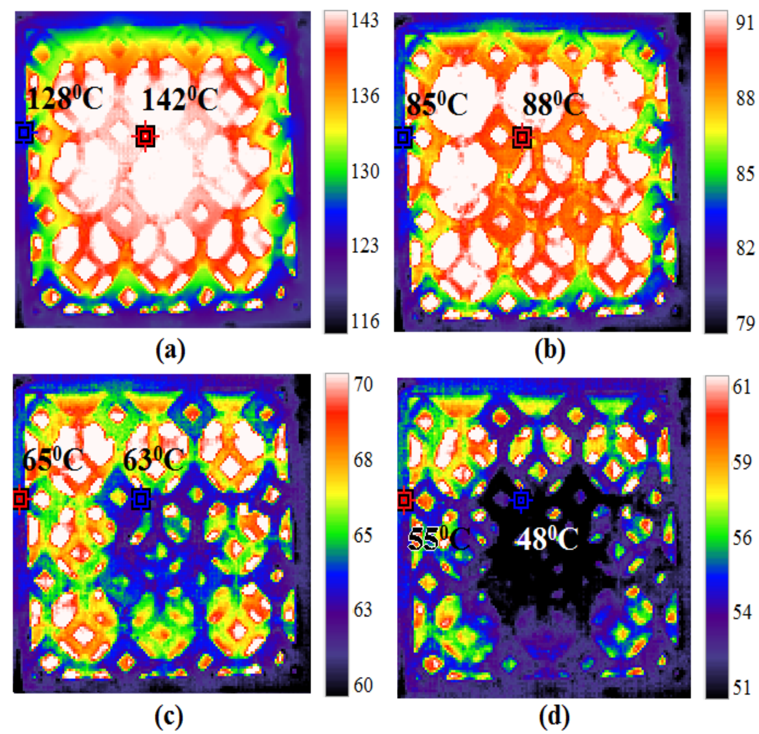
IR Camera

Conduction vs. Convection

Cubic Array



Tetradecahedral Array



2.3 kW/m²: 20, 40, 60, 80 L/min

Heat Exchanger Efficiency

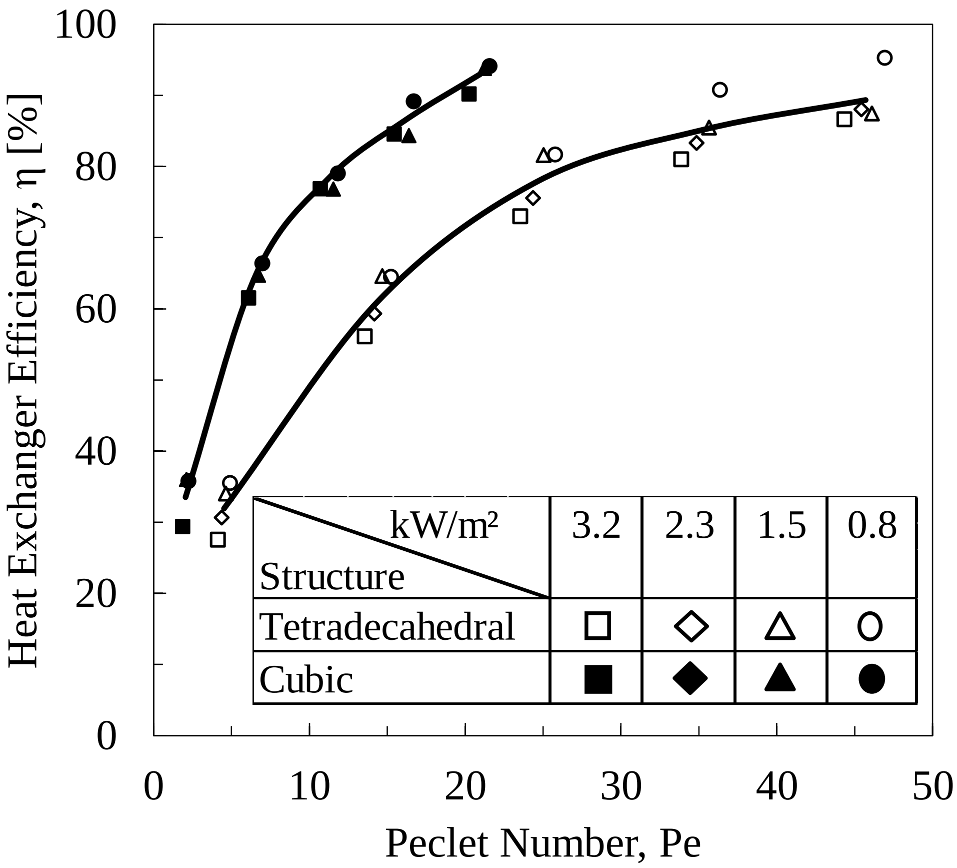
Peclet Number

$$Pe = \frac{Q_{conv}}{Q_{cond}} = \frac{\dot{m}c_{p,a}}{k_s(1-\varepsilon)H}$$

Increase of enthalpy

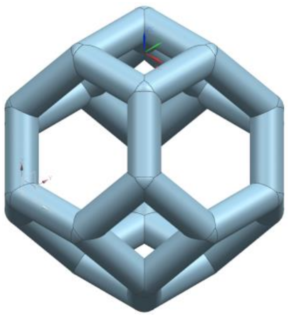
$$Q = \dot{m}c_{p,a}\left(T_{in} - T_{out}\right)$$

For given flow rate *Pe* smaller for cubic array because ε is lower. Convection more dominant for tetradecahedral than cubis array.

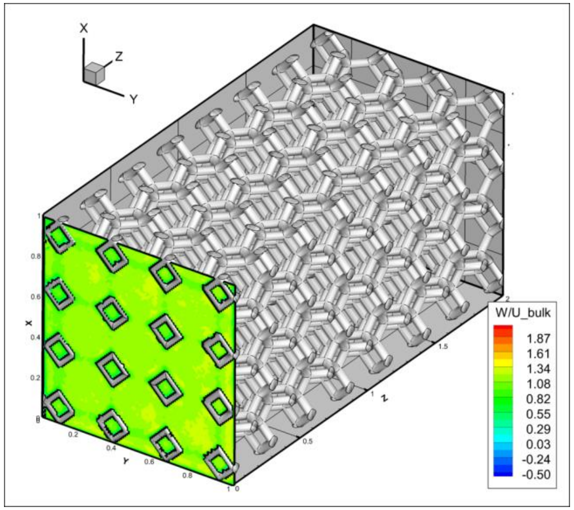


More complexity: Tetradecahedral grid

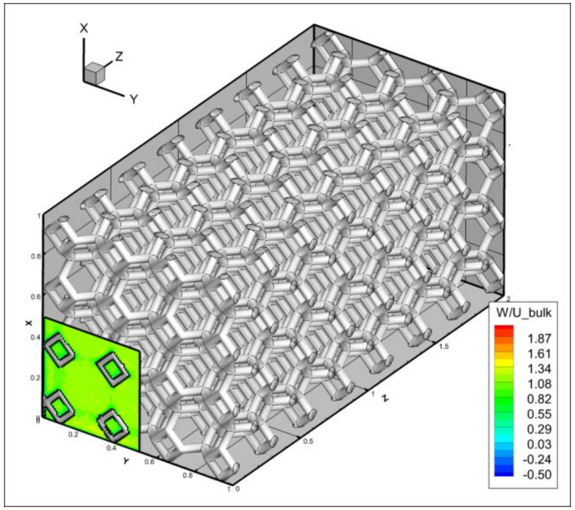
- Flow rate = 62 l/min @ 30°C, U_{bulk}=0.109m/s
- MRV parameters
  - Field of view (FOV): 158x100x100mm³, 1x1x1mm³ resolution
    → 1.58mio vectors
  - 3 scans averaged (improved SNR), 17 min/scan



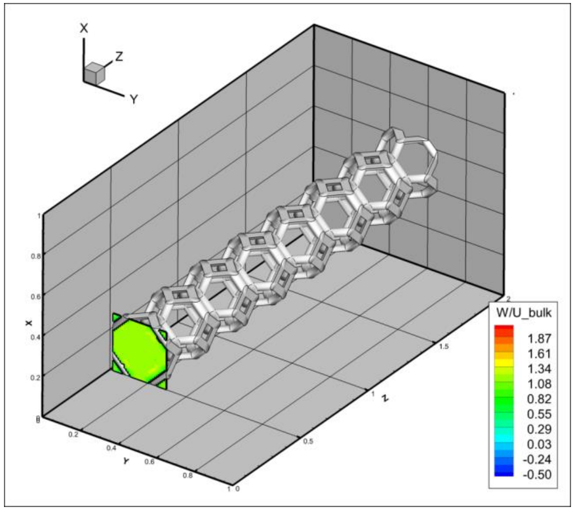
FOV - MRV



Domain - CFD

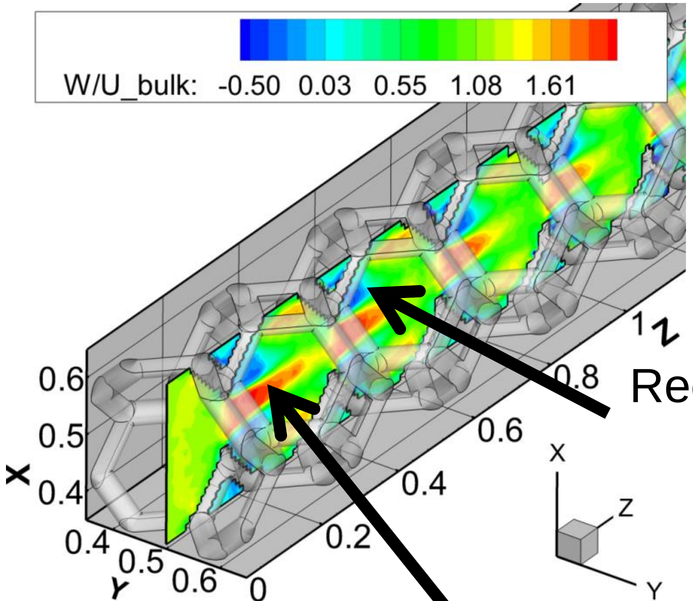


MRV – Data centered



Similar flow features as in the Pin Fin Array

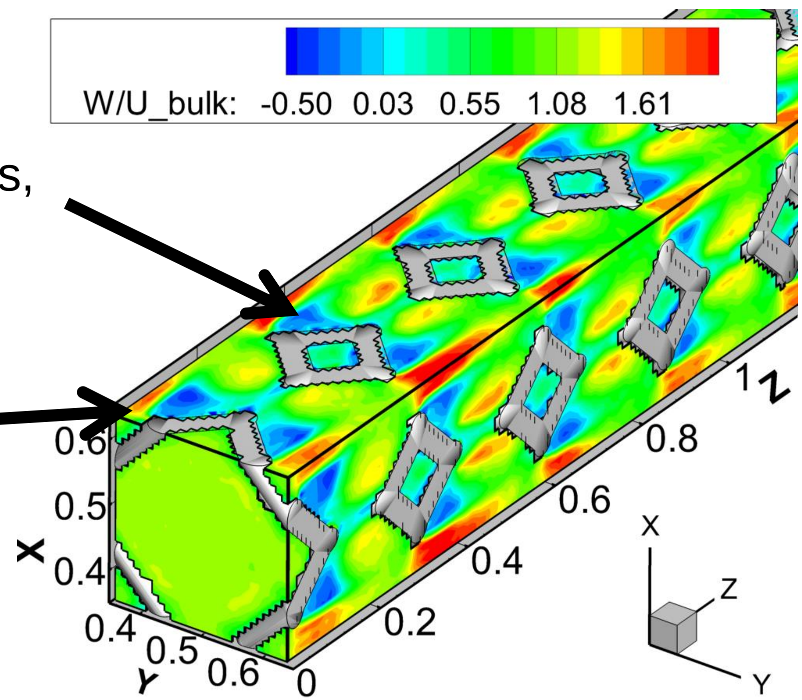
flow through the element center



Recirculation zones, hot spot

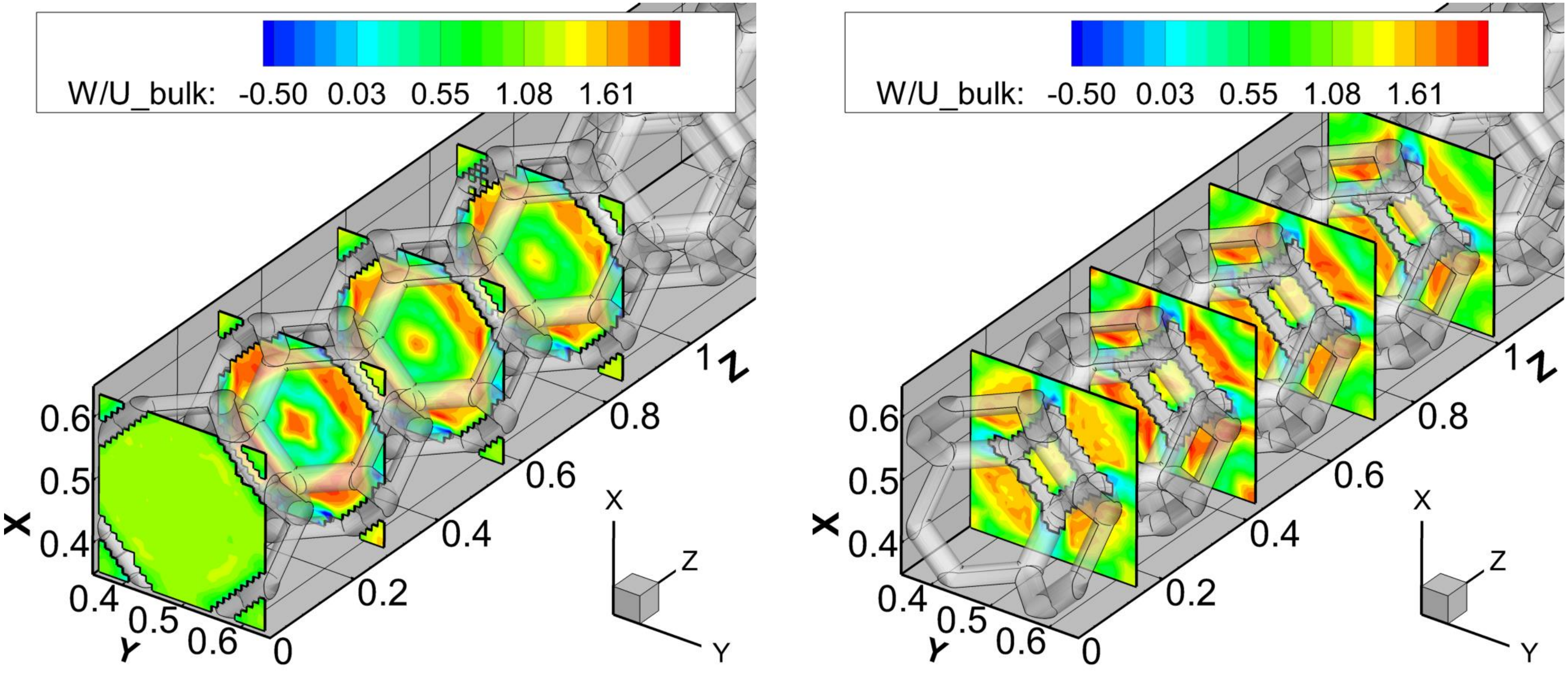
High speed jets

flow at the element surroundings

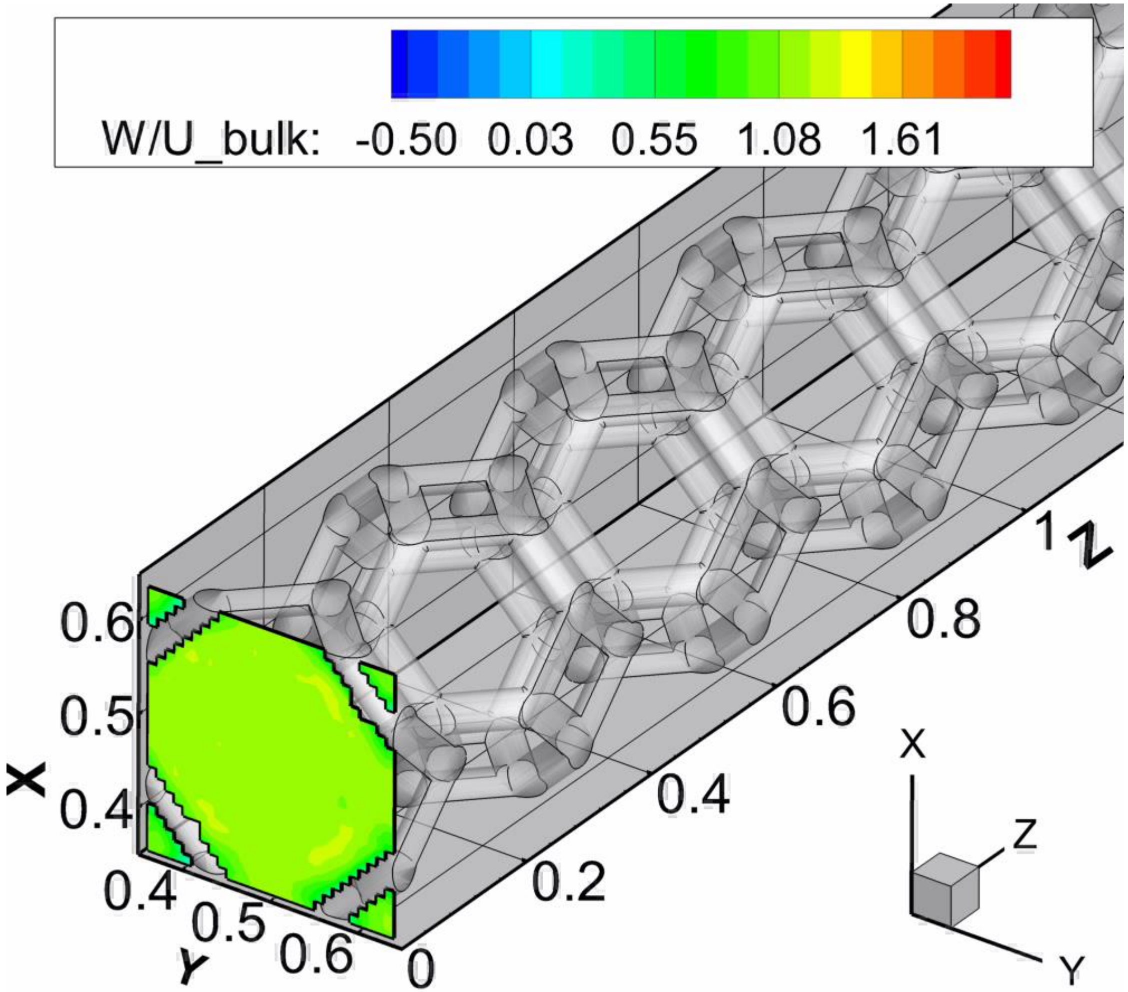


Development of flow field

- Flow fully developed after 3 tetradecahedral elements



Flow field development



CFD simulation

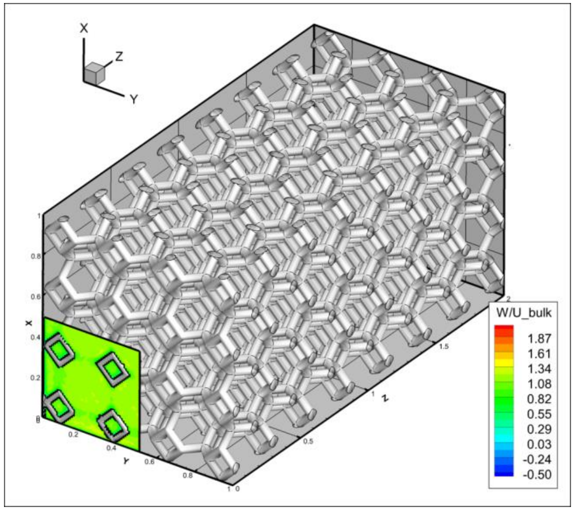
Notes on numerical methods

- Scaling of model: MRV:SIM = 3.9 : 1
  - Constant Reynolds Number
  - Velocity ratio: MRV:SIM = 0.109 : 0.4251 [m/s]
- Numerical Method: FVM, laminar, steady state (SIMPLE algorithm)
- Numerical Software: OpenFOAM 2.2.x / 2.2.1
- Gradient schemes: Linear
- Divergence schemes: Upwind
- Symmetry (reduced CFD domain)

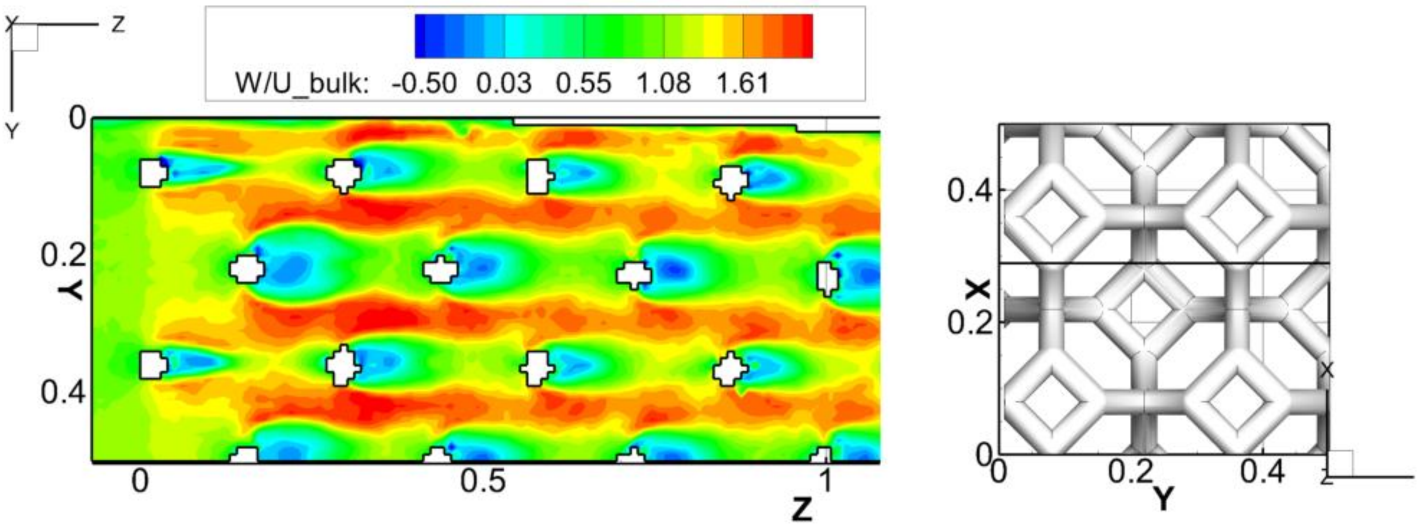
Mesh

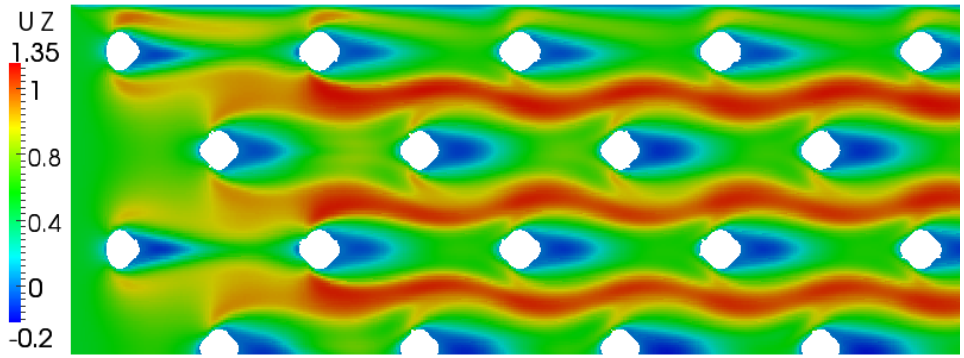
- Type: unstructured
- Generator: snappyHexMesh
- Cell Count: 29,619,795
- Max Skewness: 1.16

CFD Domain



MRV vs. CFD


W/U_bulk: -0.50 0.03 0.55 1.08 1.61
Y
Z
0
0.2
0.4
0.5
1
X
0.4
0.2
0


U Z
1.35
1
0.8
0.4
0
-0.2

Optimization Strategy

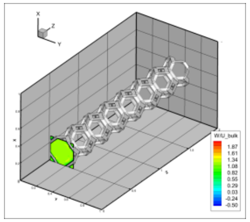
- Overall concept
- Appropriate indicator functions
- Objective functions (global/local)
- CFD/MRV validation
- Optimization strategy

Design factors

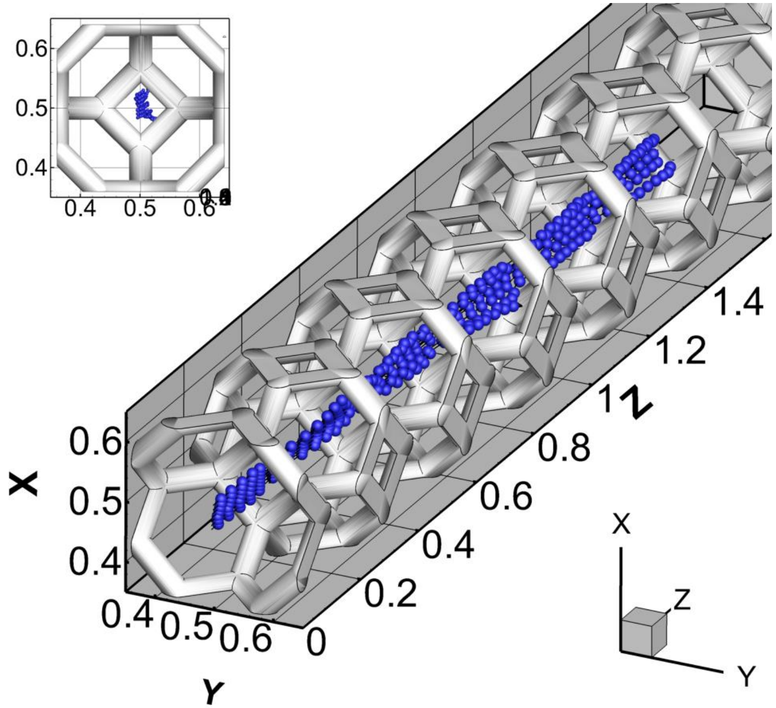
- Strut geometry
- …..

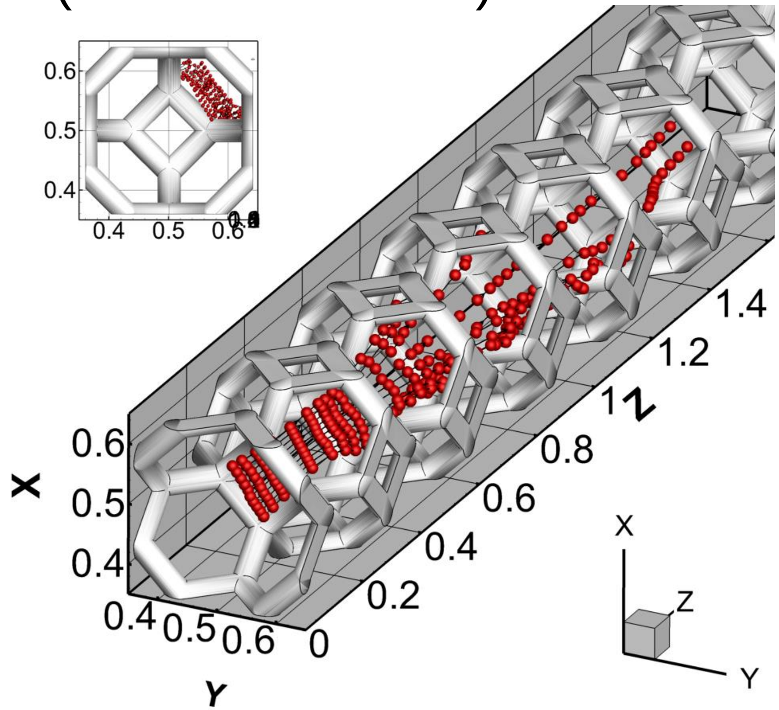
Goodness factor: $$\frac{i}{j} = \frac{Nu\,\mathrm{Pr}^{-1/3}}{f\,\mathrm{Re}}$$

Streamlines



- Streamlines in center of structure (blue) stay in line
  → maybe disadvantegeous for heat transfer
- Streamlines off center of structure (red) diverge
  → increased diffusion (and heat transfer)





New horizons: Three-dimensional temperature mapping using MR Thermometry

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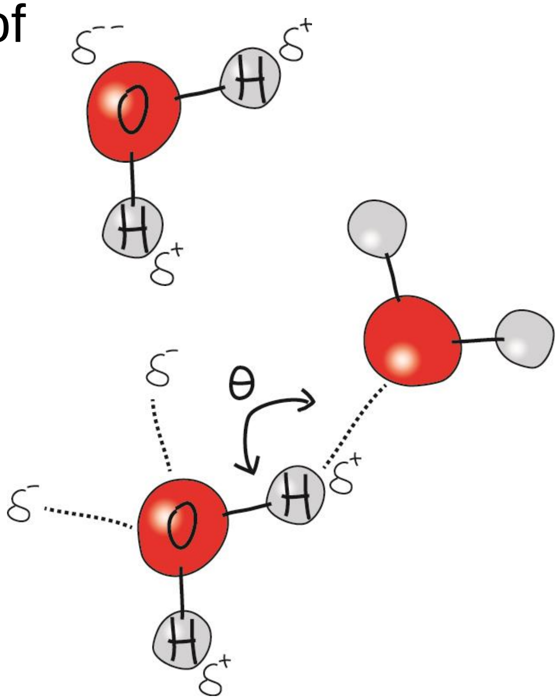
To recall: Important for MRI is the magnetic reaction of the Hydrogen core (proton) of the H_2O molecule



- H_2O = dipol
- Liquid H_2O = Varying hydrogen bonds
- Increased water temperature leads to less stronger hydrogen bonds (bonds bend, stretch and break)
  - →The free electron can screen the hydrogen more efficiently
  - →This reduces the local effective magnetic field
  - →Larmor frequency decreases
- $|\omega_{50°C} - \omega_{20°C}|$ = 38.3Hz (only!)
  - Only measurable in the MR signal phase
  - Phase-difference $\Delta\phi$ is proportional to water temperature difference to a reference scan

$$\omega(T) = \gamma B_{eff}(T)$$

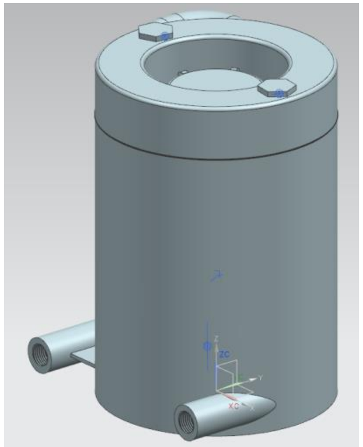
$$\Delta\phi = \phi_{ref}(T_{ref}) - \phi(T_i)$$

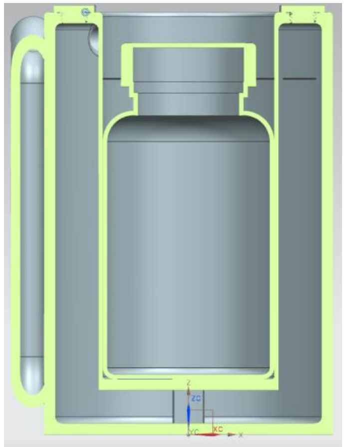
Thanks for your attention

A first shot…

- Heated bottle filled with concentrated water inside a heat exchanger
  - Concentrated water prevents free convection flow
- MR Thermometry sequence:

  → $T_{MRT,mean}$ = 19.06+/-0,39°C

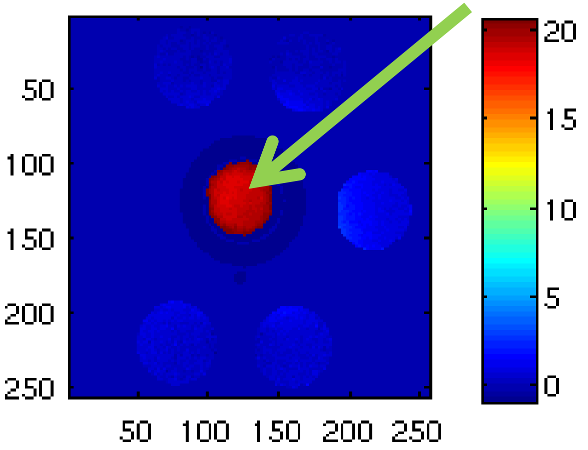




- Fibre optical temperature transducer:

  → $T_{Luxtron}$ = 19.10°C

Measured temperature field (2D)

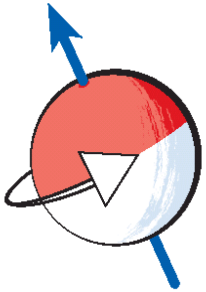


- Goal of DFG funded project:
  - Measuring 3D temperature fields together with 3D velocity fields

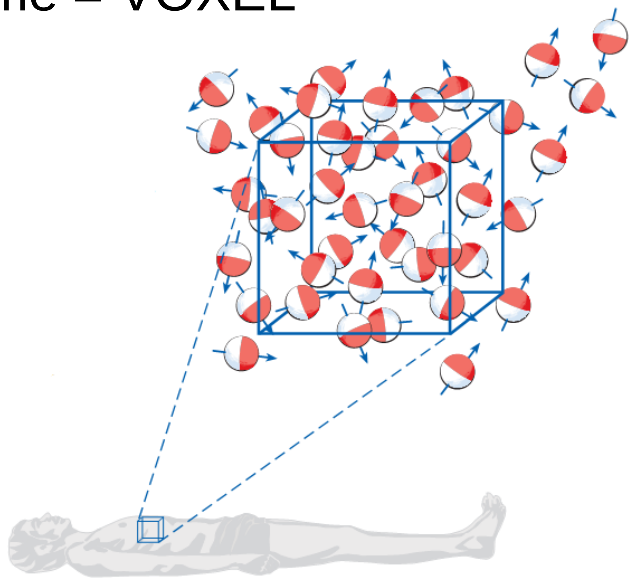
Spin

- The spin is a quantum-mechanical characteristic of atomic particles.
- Uneven mass number → net spin!
- A rotating charge is always magnetic.
- Spins are distributed in the field
- An ensemble of spins in a small volume = VOXEL

Spin of a proton

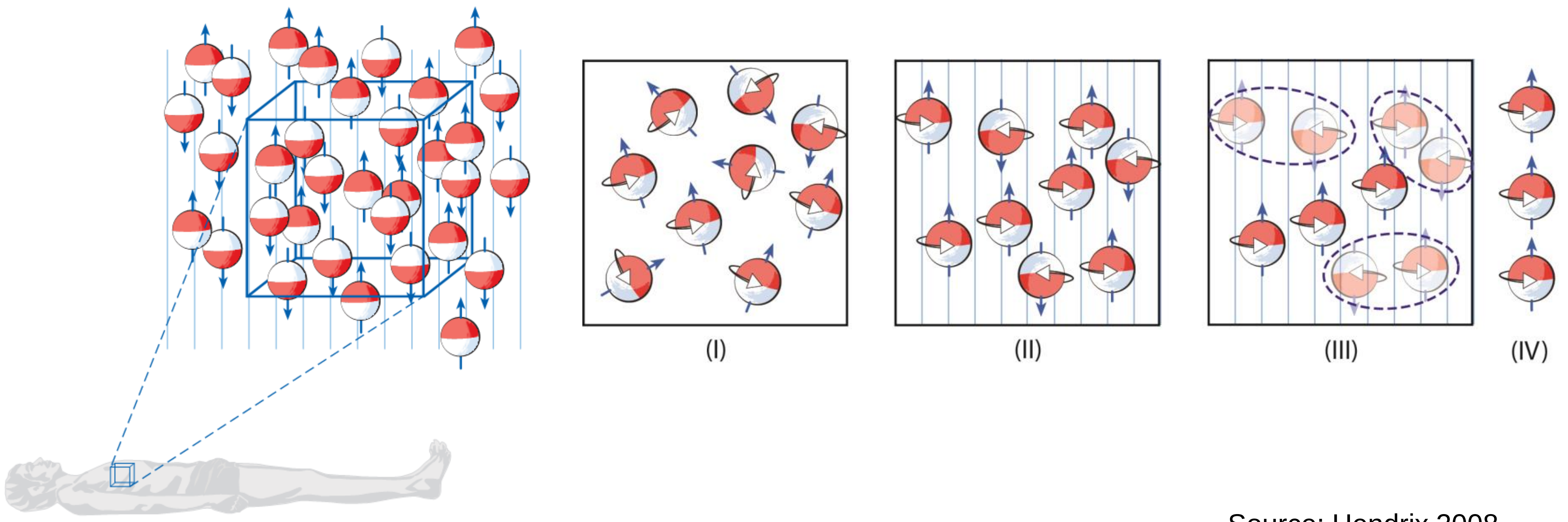


Source: Hendrix 2008



Spin in a magnetic field

- In the presence of a strong external magnetic field the nuclei align along the field direction.
- More up-spins than down-spins → net magnetization



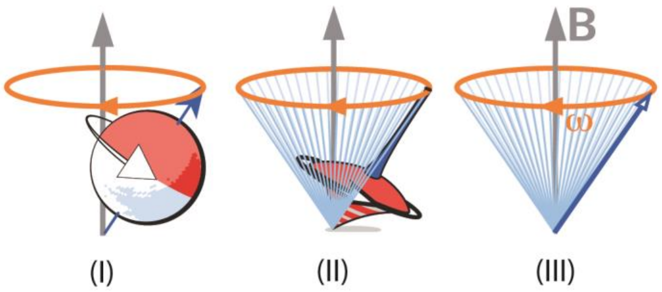
Source: Hendrix 2008

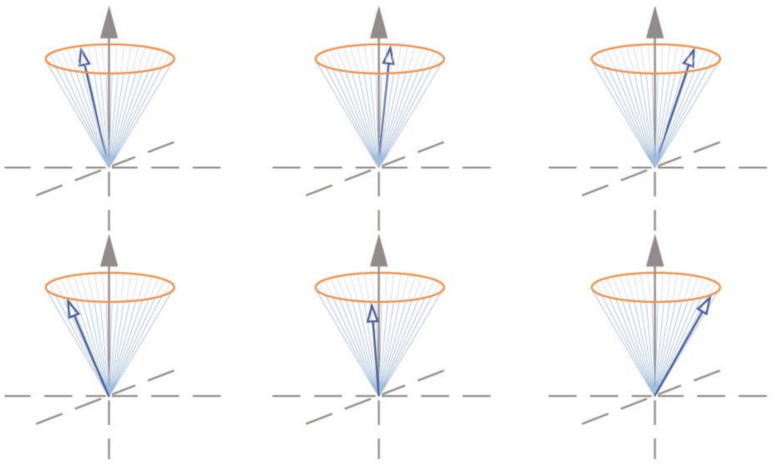
Spin precession

- The spin magnets do not align steadily. They **process**.
- The spin precession takes place at a fixed frequency depending on the magnetic field strength.
  → Lamor frequency

$$\omega_0 = \gamma B_0$$

- All spin magnets precess with same frequency but different phase
  → **no resulting magnetization**!





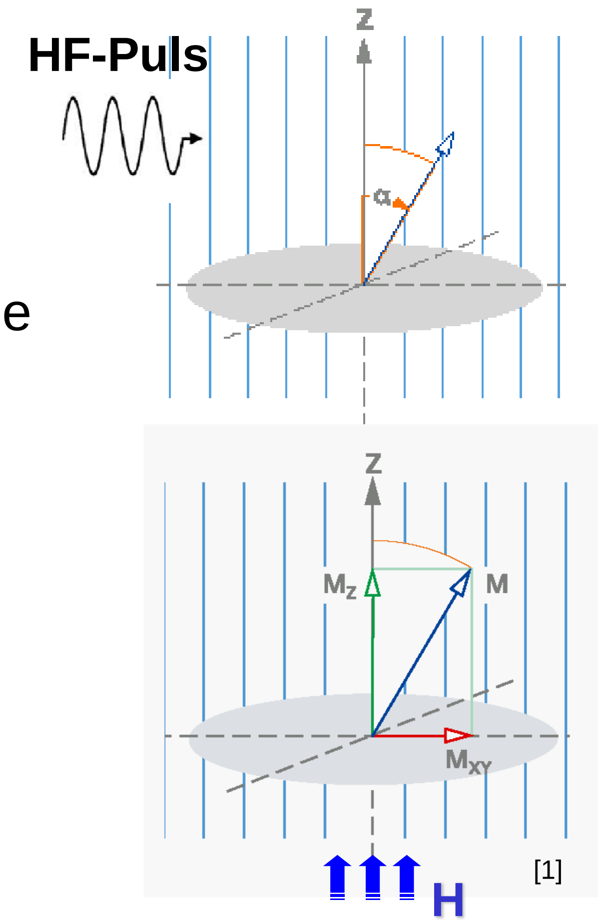
Source: Hendrix 2008

Measuring the Spin

- No magnetization can be measured!
  However all spins precess out of phase…

- HF pulses (circular polarized wave) at the precession frequency disturb the equilibrium of the spins.
  → The spin flips at angle α
  → A transverse magnetization is achieved

- This produces a magnetization vector M with
  - Longitudinal component (M_z)
  - Transverse component (M_xy)

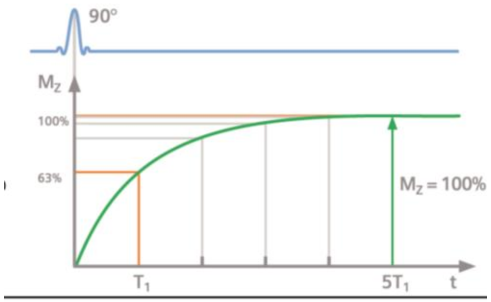


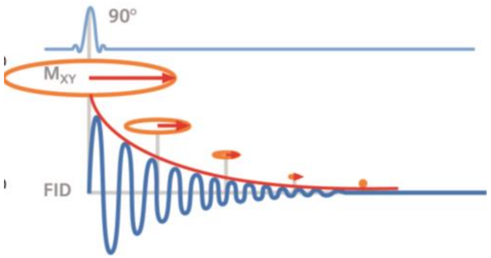
Source: Hendrix 2008

Relaxation and Decay

- Spin-lattice relaxation (or T1 relax.) of M_z
  - Time constant T1
  - Due to interactions with surrounding atomic neighborhood
- Decay of transversal magnetization (or T2* relaxation)
  - Time constant T2*
  - Local precession frequency differences lead to spin-spin phase dispersion

- Different relaxation types lead to different contrast of tissue





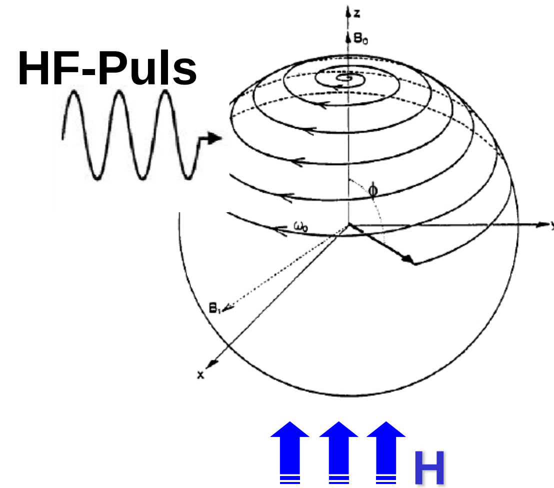
Source: Hendrix 2008

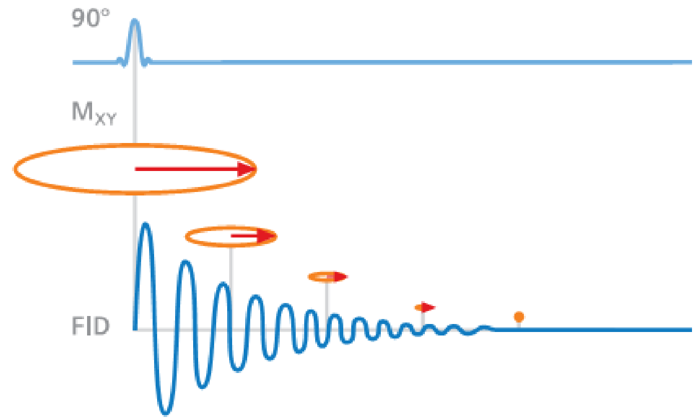
MR-Signal

- 90°-rf pulse
  - All spins in phase
  - M_z=0
  - M_xy rotates with Larmor frequency

- Transverse magnetization is equal to a rotating magnet
  → Dynamo principle
  → induces electric current in a coil

- MR-Signal=Free induction decay of M_xy

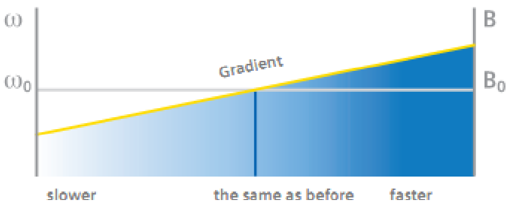




Source: Hendrix 2008

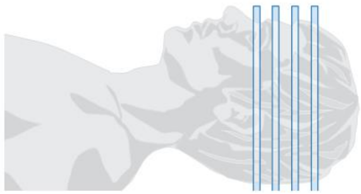
Measuring volume in 3D

The precession frequency is depending on the magnetic field strength

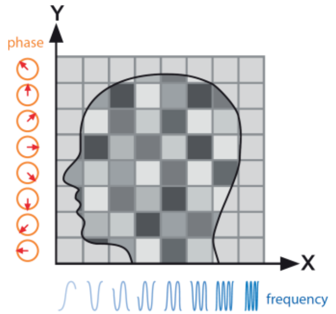


By applying gradients to the field strength

- slices of the volume can be selected during excitation (slice selection)



- Local precession frequencies can be modified (x-coordinate/frequency encoding)
- Phase differences can be obtained by temporal gradients (y-coordinate/phase encoding)

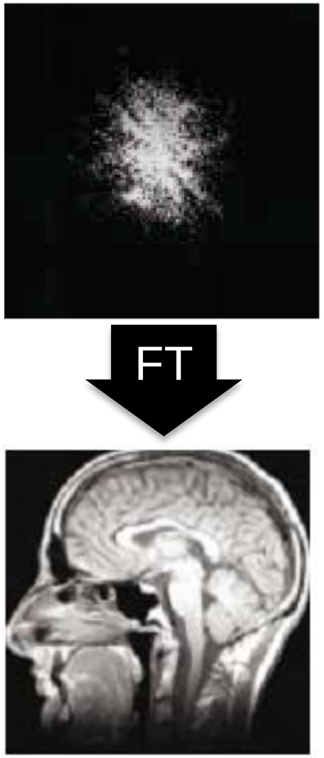


Source: Hendrix 2008

From the signal to the image

The complex signal is stored in k-space.

Two Fourier Transforms reconstruct the original magnitude of the signal in every voxel. That gives the image.

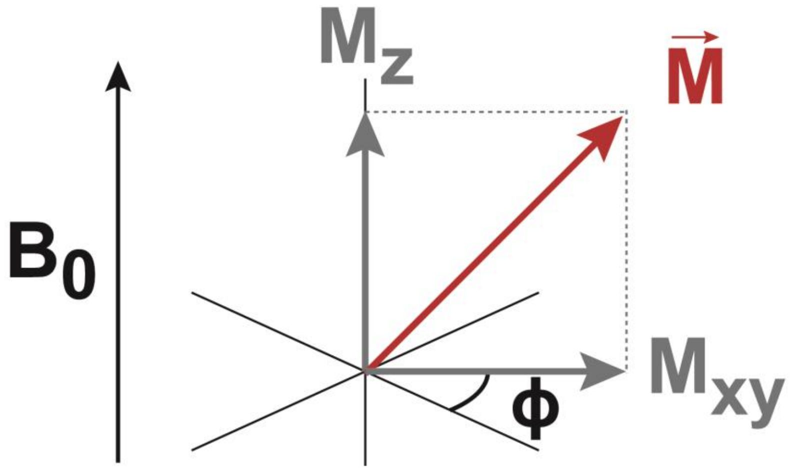


Source: www.siemens.de

Phase Contrast Imaging

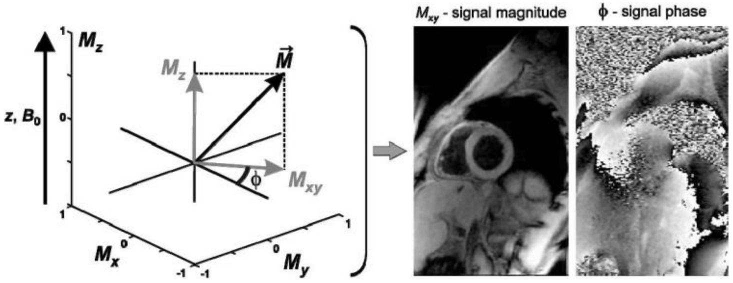
- Not used so far is the original phase ϕ of the signal in every voxel

=> *Phase Contrast Imaging → Velocities*



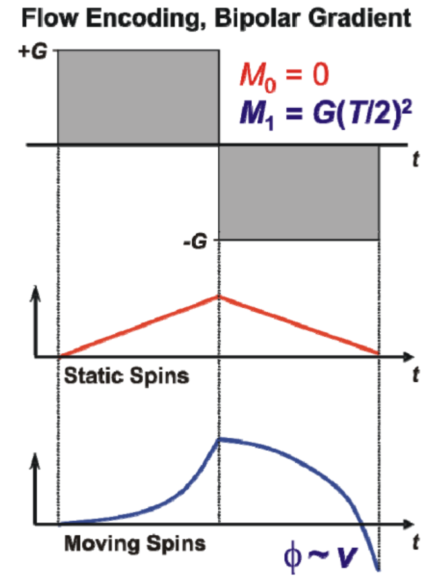
Measuring Velocities 3C

The phase of the MR-signal is sensitive for fluid motion.



By applying a bipolar gradient pulse,

- Static spins acquire phase and lose it again
- Moving spins acquire **less** phase than they loose



One measurement per direction (3C) necessary.

Source: Markl et al.