Experimental study of the flow helicity in blood vessel models with MRI

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Introduction

- Non-invasive methods:
  - Doppler ultrasonography
  - Computed tomography (CT)
  - Magnetic resonance imaging (MRI)
- V. P. Kulikov, R. I. Kirsanov, 2013
- A. D. Yukhnev, Ya. A. Gataulin, et al., 2015
- A. Frydrychowicz, et al., 2009
- M. Markl, et al., 2010
- L. A. Bokeria, et al., 2013
- and others…

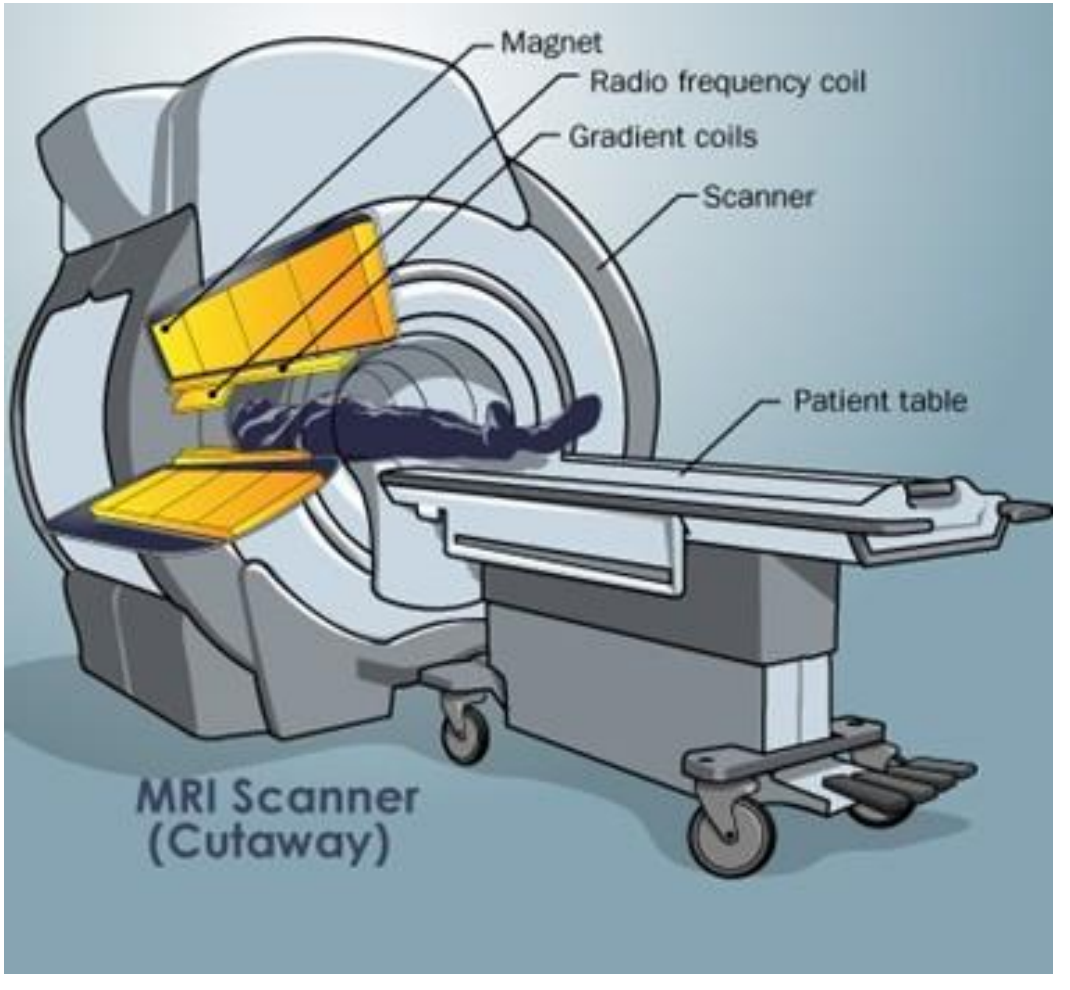
Aim

- Investigation of the velocity field of physiological flows with MRI:
  - Development of the research protocol.
  - Development of the post-processing software.
  - Comparison with the numerical simulations.

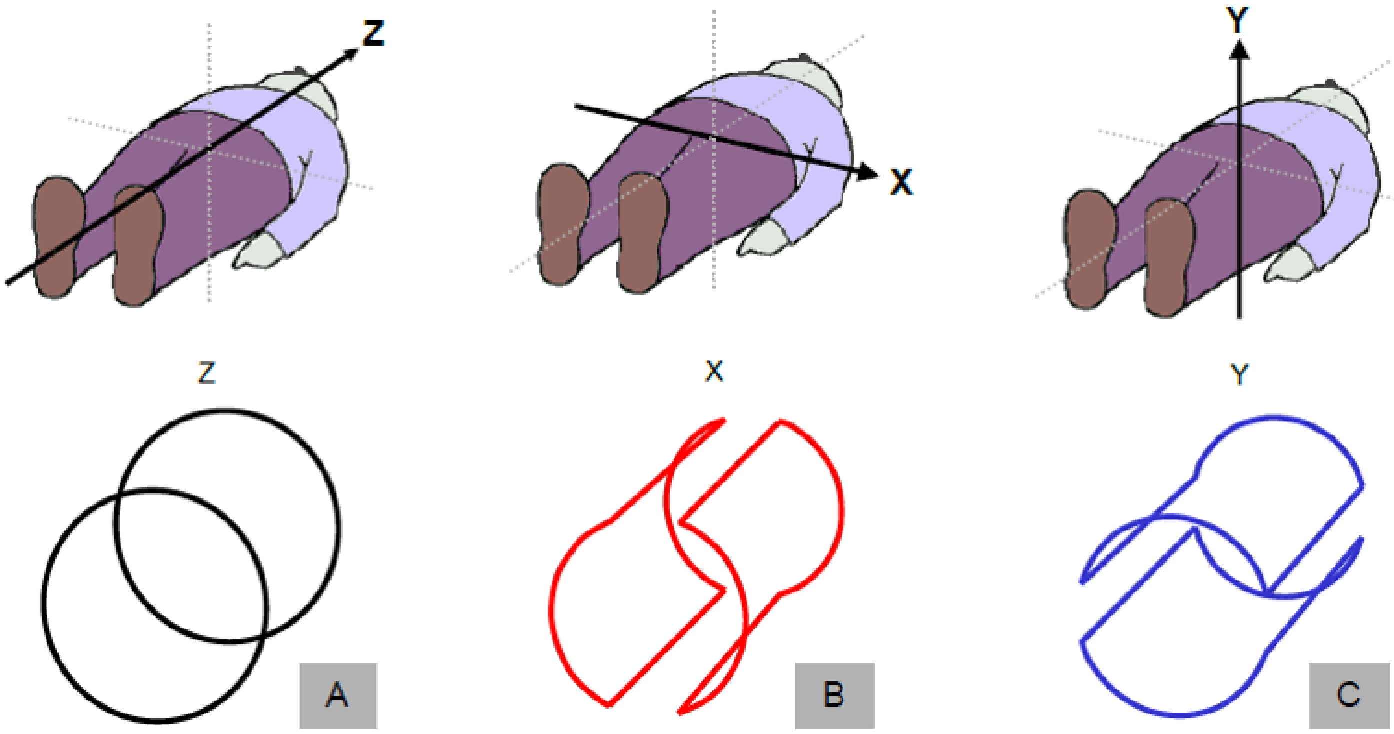
Experimental setup

- MR scanner Philips Ingenia 3T (ITC SB RAS)
- Programmable pump CompuFlow 1000MR
- Silicone models
- Blood mimicking liquid

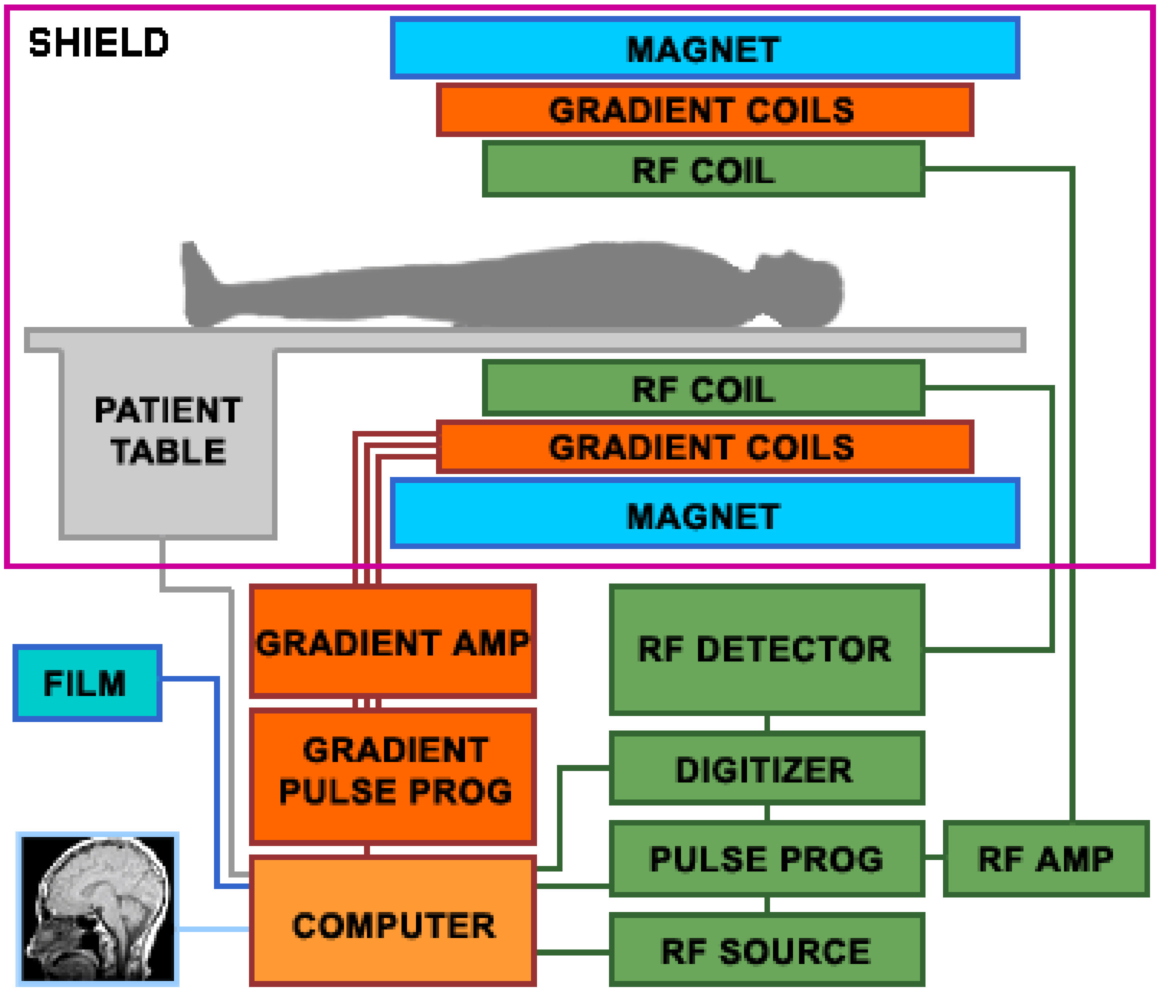
Magnetic resonance scanner



Gradient coils



MRI schematics

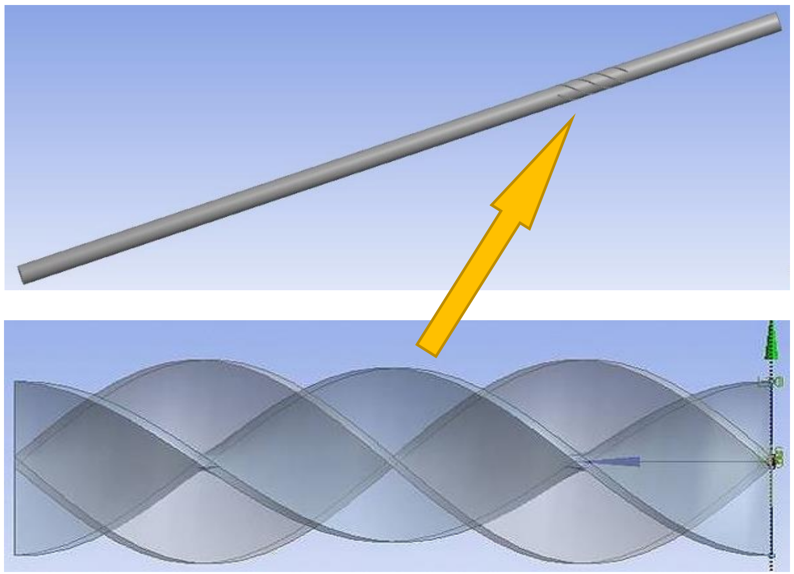


CompuFlow 1000 MR

Shelley Medical Imaging Technologies

- Programmable flow rates
- Fluid: glycerol solution (density 1000 kg/m³, viscosity 0,004 Pa·s)

Models



Silicone tube with swirl generator

Giant aneurysm on internal carotid artery

Common carotid artery bifurcation (Shelley Medical Imaging Technologies)

4D Qflow by Philips

DICOM data

Data structure

- Each measurement in 4D-Qflow results in 4 series of DICOM images:
  - PCA/M, PCA/P-RL, PCA/P-FH, PCA/P-AP
- Each series consists of spatial-temporal slices with values of two types (density and velocity):
  - In total: 2 × (time steps) × (number of slices)
- Each DICOM image: metadata and data

Image structure

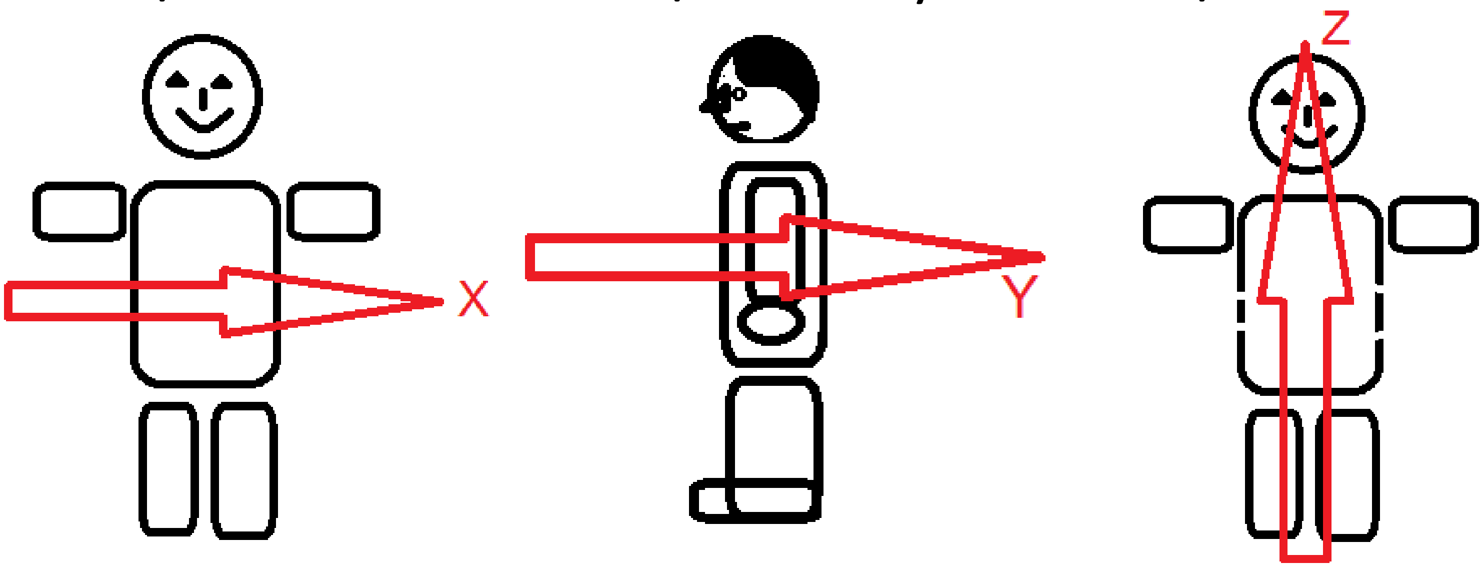
- Metadata:
  - TimeStepNumber = "(2001,1008)"
  - SliceNumber = "(2001,100A)"
  - ImageType = "(2005,1011)"
  - "ImagePosition"
  - "ImageOrientation"
  - "SlicesSpacing"
  - "SliceLocation"
  - "PixelSpacing"
  - "TriggerTime"
- Data: matrix with one velocity component

Flow parameters

- Metadata:
  - TimeStepNumber — number of the temporal step
  - "ImagePosition" — coordinates of the pixel (1, 1)
  - "ImageOrientation" — row and column unit vectors
  - "PixelSpacing", "SlicesSpacing" — (dy, dx, dz)
  - "TriggerTime" — list of time moments

Reconstruction of the velocity field

- Each series contains one velocity component
  - PCA/P-RL — x PCA/P-AP — y PCA/P-FH — z

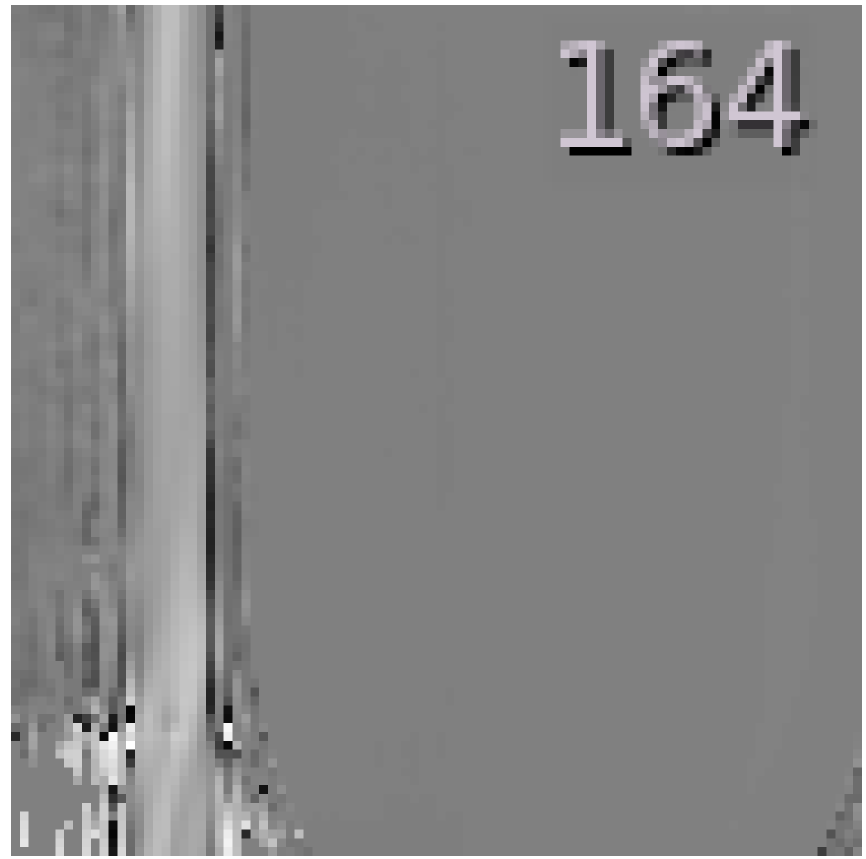


- "ImageOrientation" — rotation matrix (change of coordinates)

https://dicomiseasy.blogspot.ru/2013/06/getting-oriented-using-image-plane.html

DICOM images

Density image



Velocity component

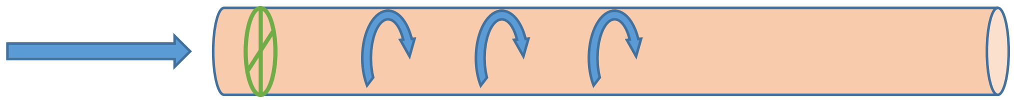
Post-processing

Results

Session 1				
	1	Swirl generator v.1	96x96x7 (280)	
Session 2				
	a-1000	Swirl generator v.1	160x160x11 (440)	
	b-1100	Swirl generator v.1	160x160x11 (440)	
	c-1300	Swirl generator v.1	240x240x20 (800)	
Session 3				
	1	Swirl generator v.1	96x96x7 (280)	
	2	Swirl generator v.1	160x160x11 (440)	
Session 4				
	2a-800	Swirl generator v.1	96x96x7 (280)	18+/-3
	2b-900	Swirl generator v.1	160x160x11 (440)	18+/-3
	2c-1000	Swirl generator v.1	240x240x20 (800)	18+/-3
	3a-800	Swirl generator v.2	96x96x7 (280)	18+/-3
	3b-900	Swirl generator v.2	160x160x11 (440)	18+/-3
Session 5				
	1	Aneurysm model	176x176x25 (1000)	12 +/- 3 ml, f = 0.5 Hz
	2	Aneurysm model	176x176x25 (1000)	15 +/- 3 ml, f = 0.5 Hz
Session 6				
	1	Aneurysm model	176x176x25 (1200)	15+/-3 ml, f = 0.5 Hz
	2	CCA bifurcation	96x96x7 (280)	15+/-3 ml, f = 0.5 Hz
	3	CCA bifurcation	160x160x11 (440)	15+/-3 ml, f = 0.5 Hz

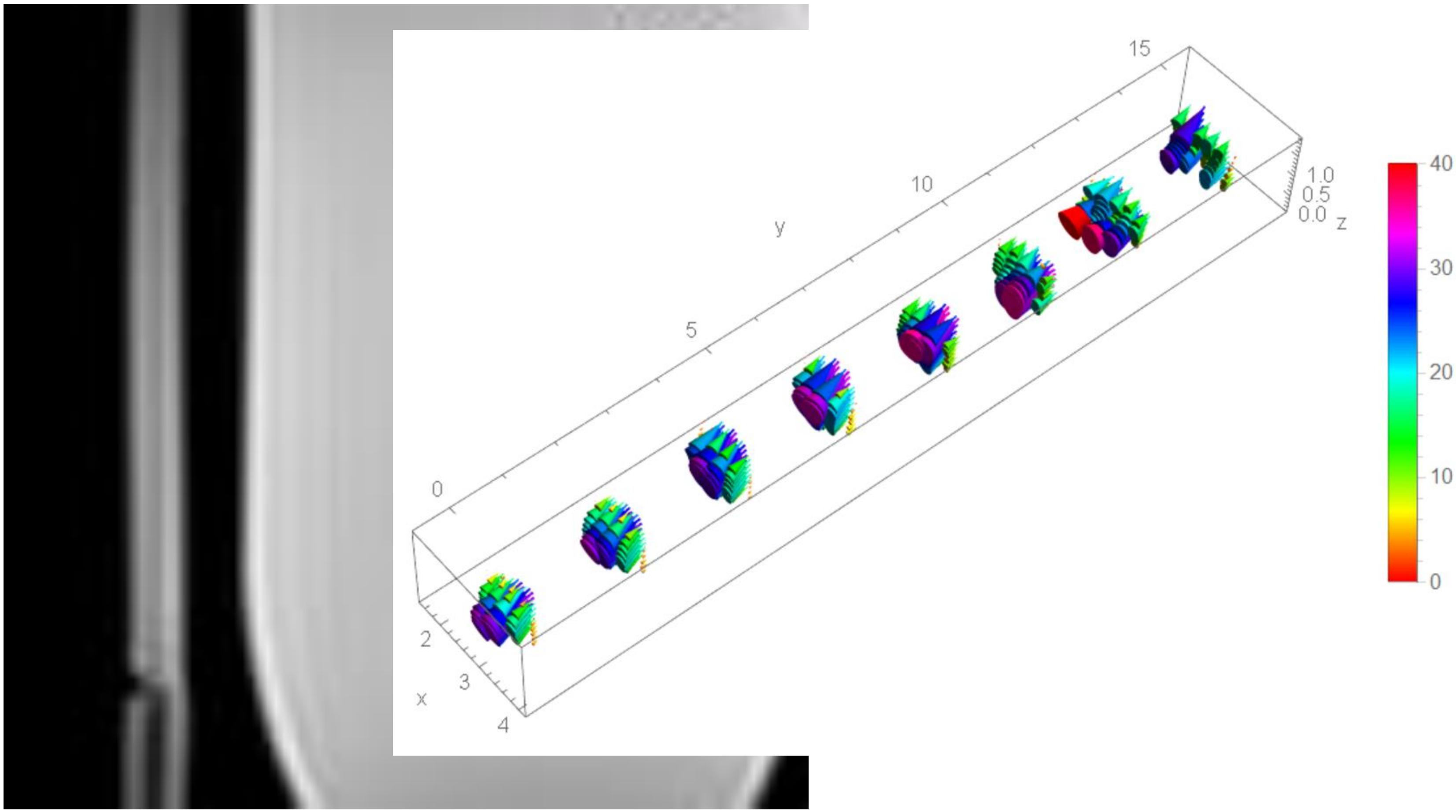
Flow in elastic tube

- Silicone tube with a swirl generator
- Flow rate: 18 + 3 sin(π*t*) ml/s, *f* = 0,5 Hz.

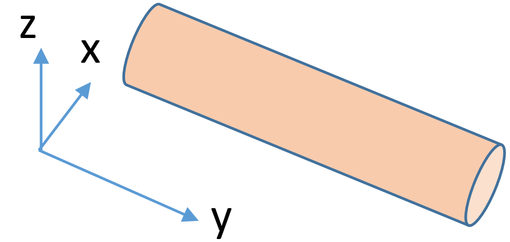


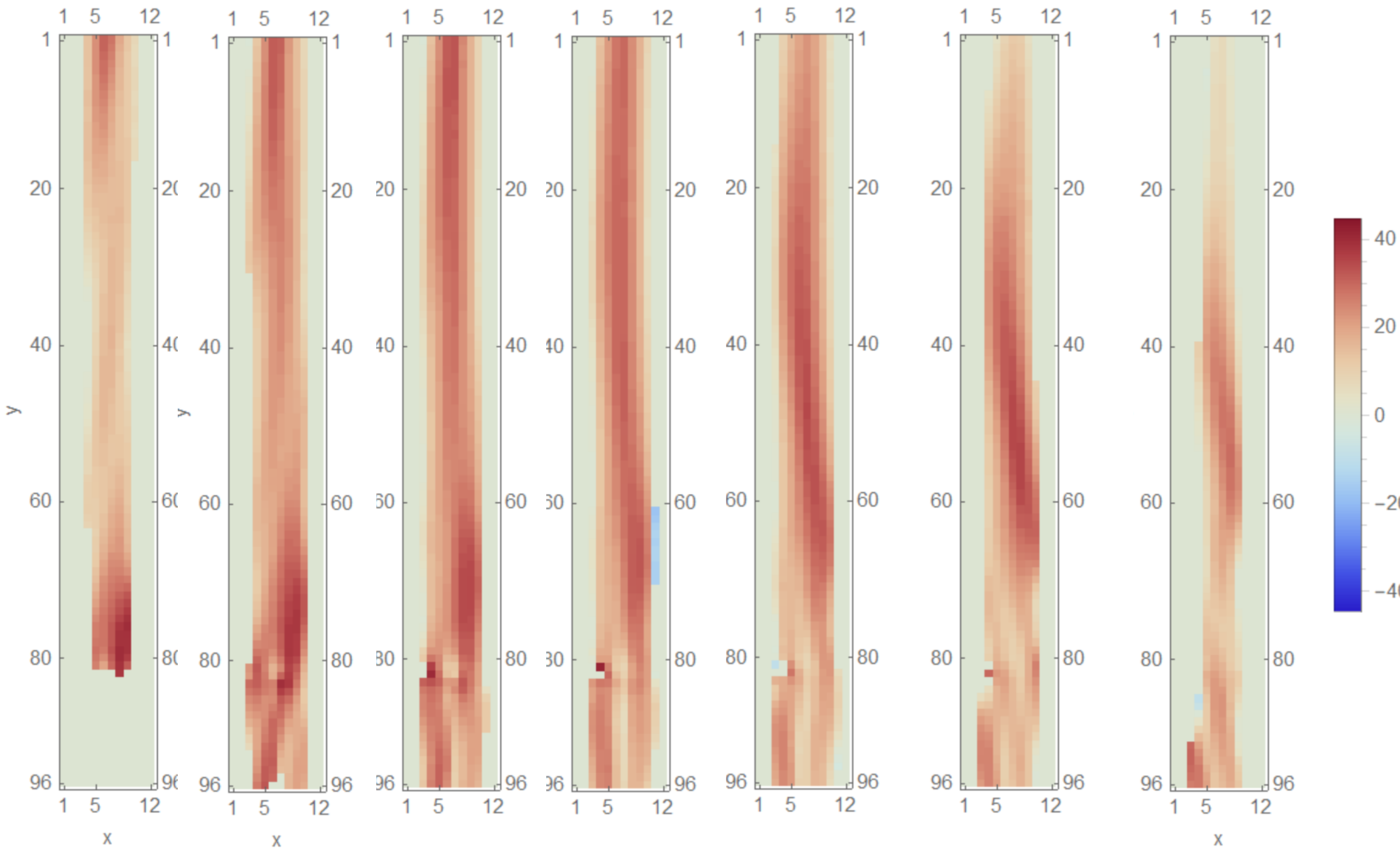
3D matrix	Time steps	Voxel, mm^3	Domain, mm^3	Files
96×96×7	20	1.56×1.56×1.5	150×150×10.5	4 × 280
160×160×11	20	0.94×0.94×1.25	150×150×13.75	4 × 440
240×240×20	20	1.25×1.25×1.25	300×300×25	4 × 800

Matrix 96×96×7



Axial velocity

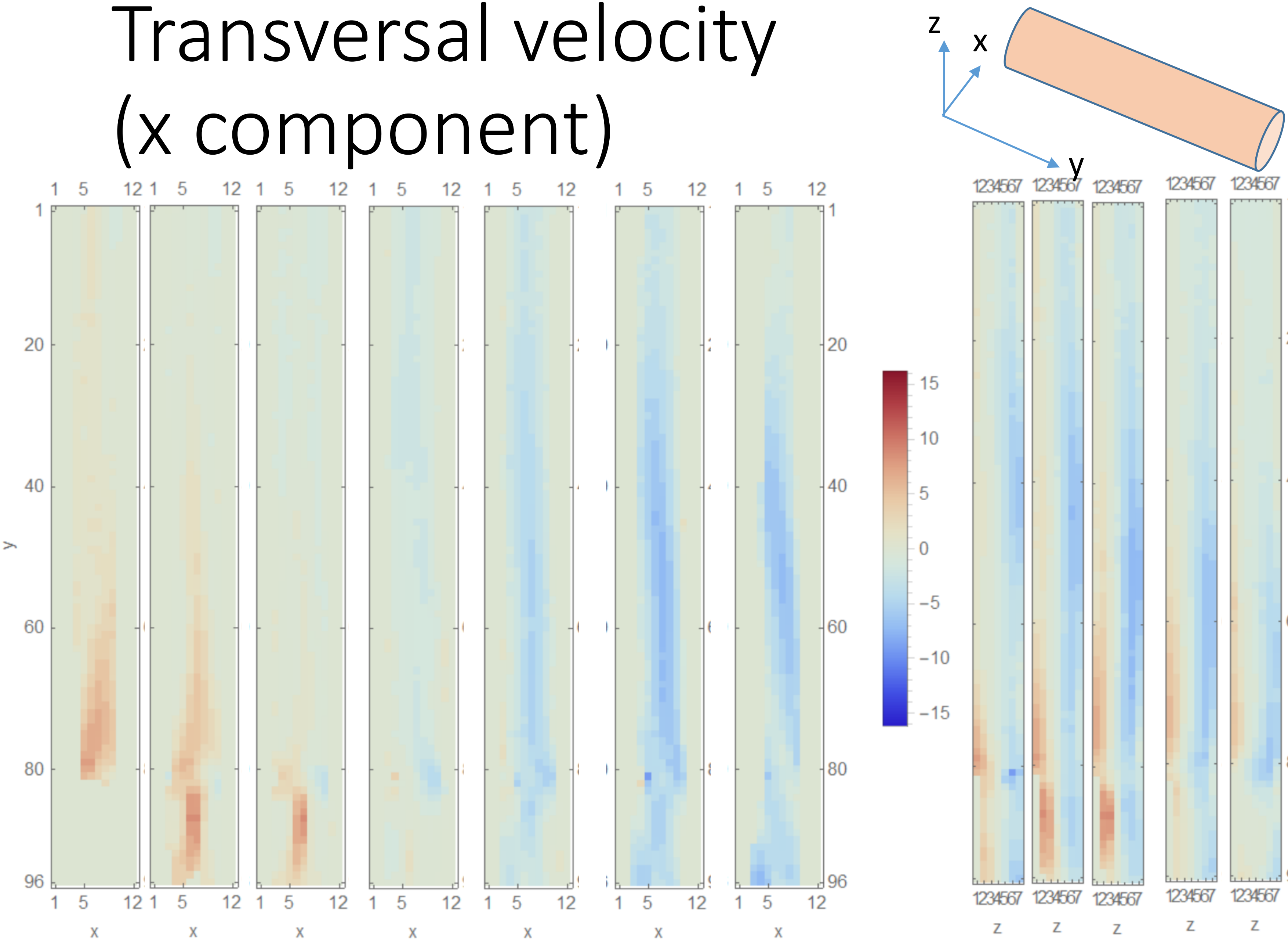




z = 1

z = 7

Transversal velocity (x component)



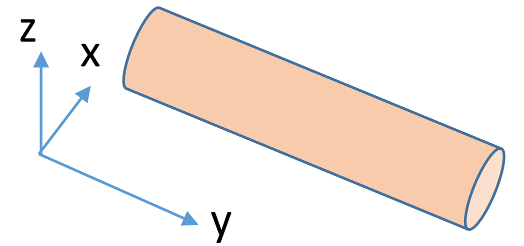
z = 1

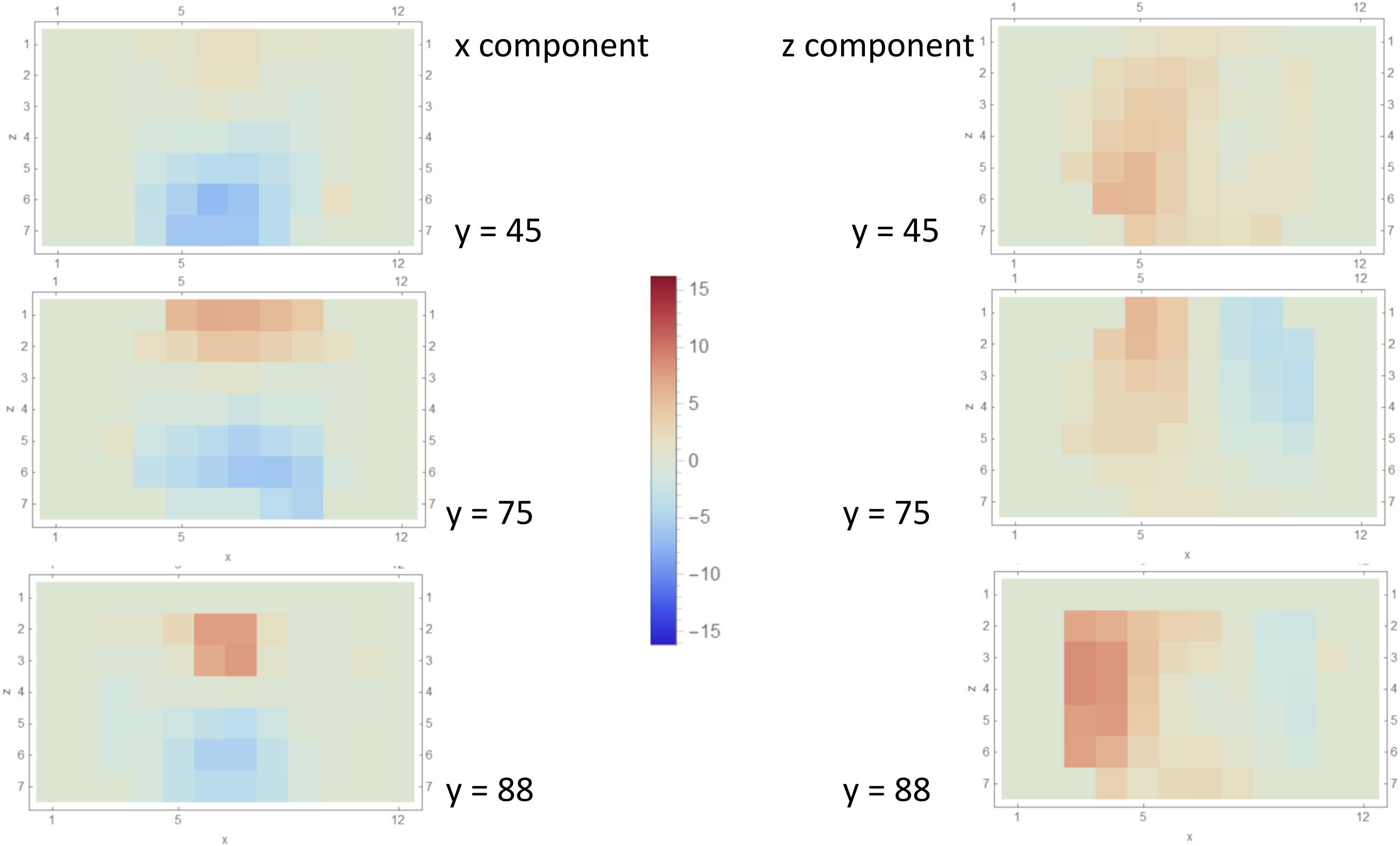
z = 7

x = 5

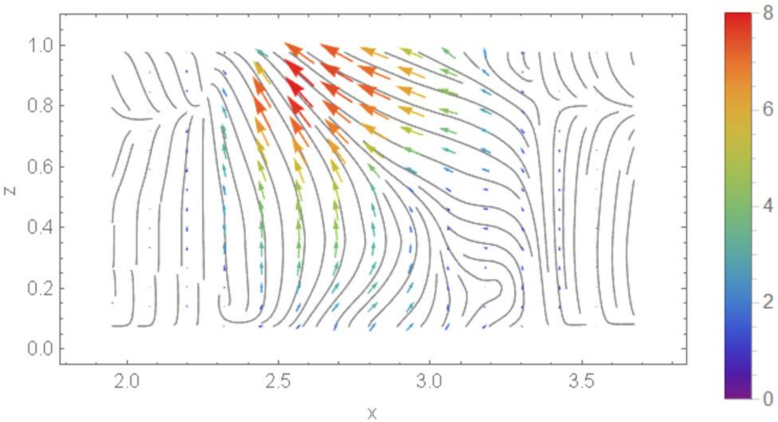
x = 9

Transversal velocity

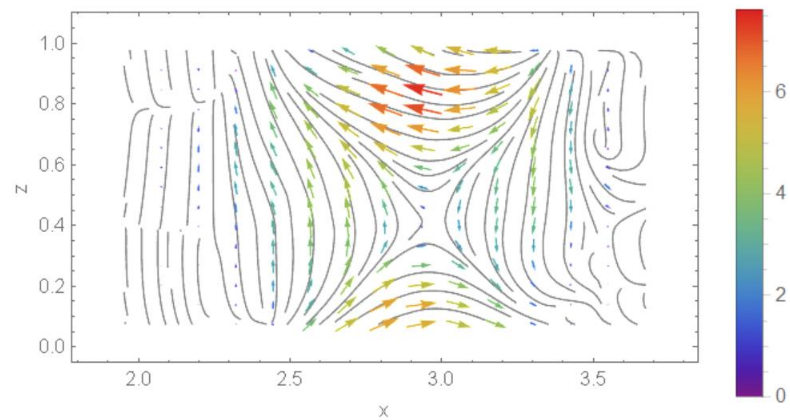




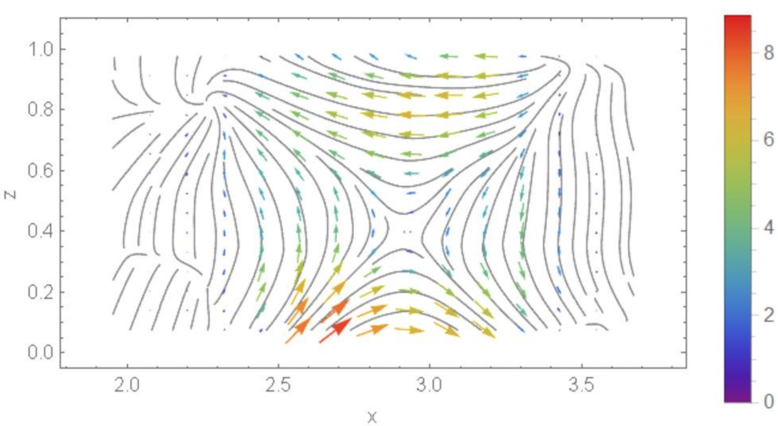
Streamlines for transversal velocity component



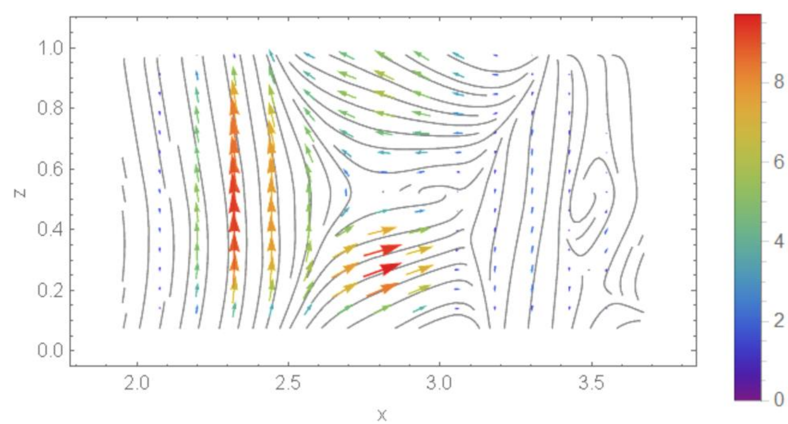
y = 43



y = 69

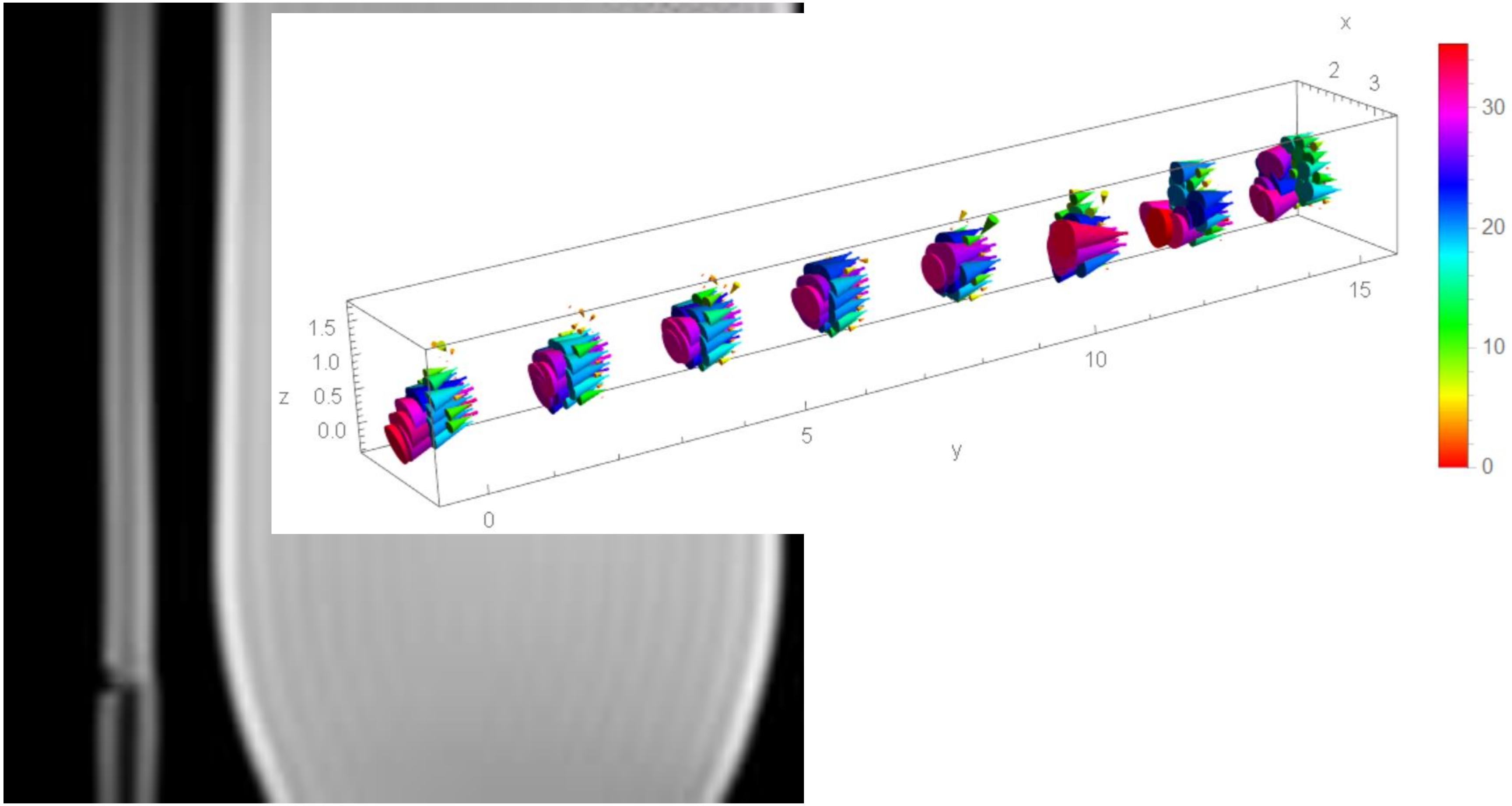


y = 75

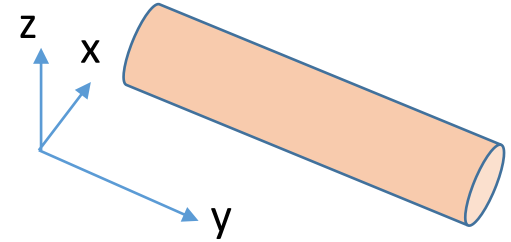


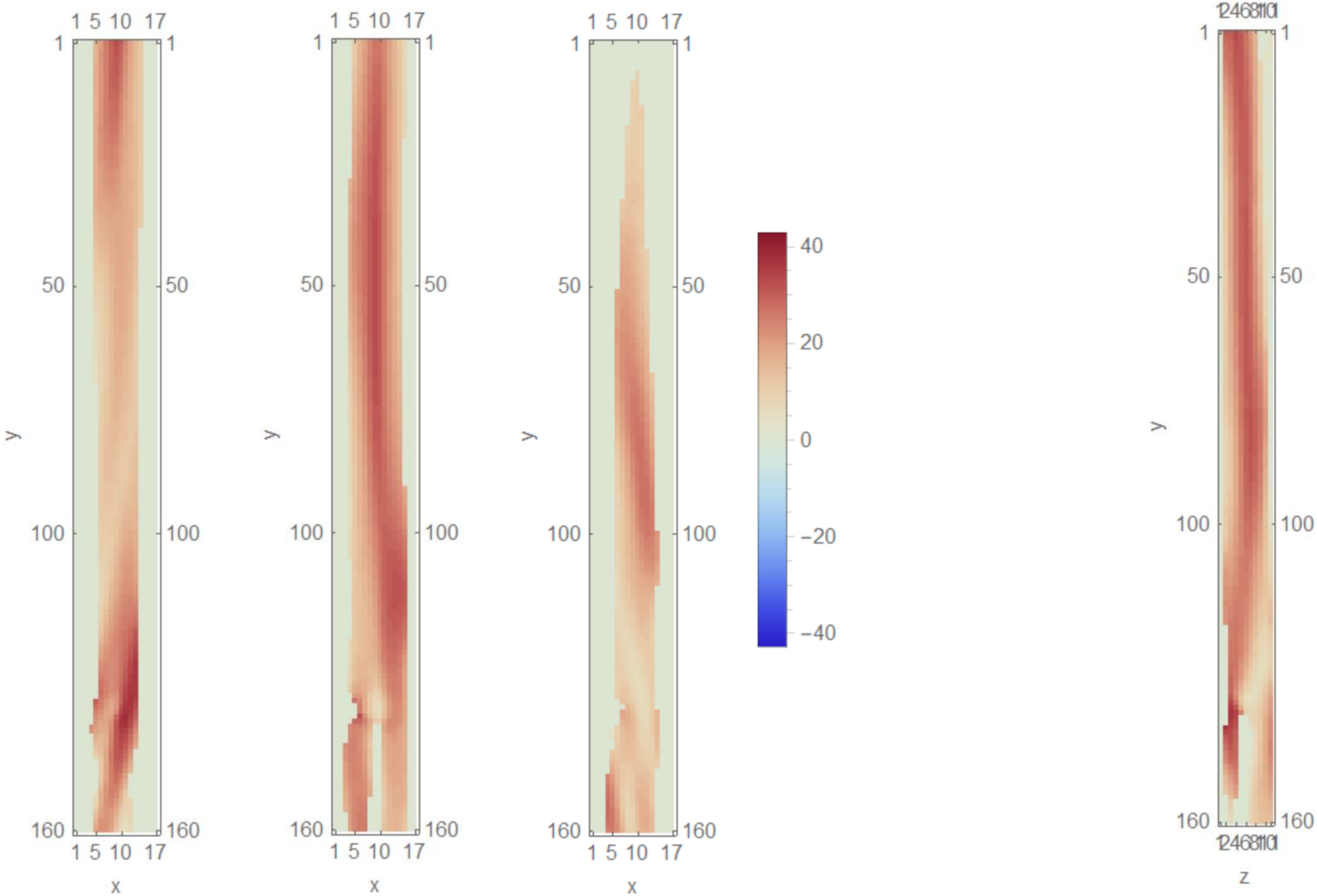
y = 88

Matrix 160×160×11



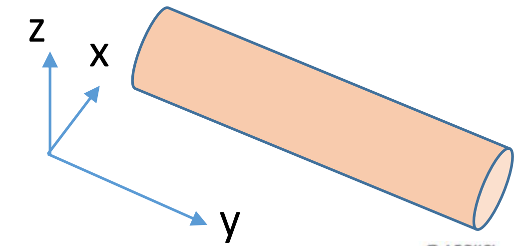
Axial velocity

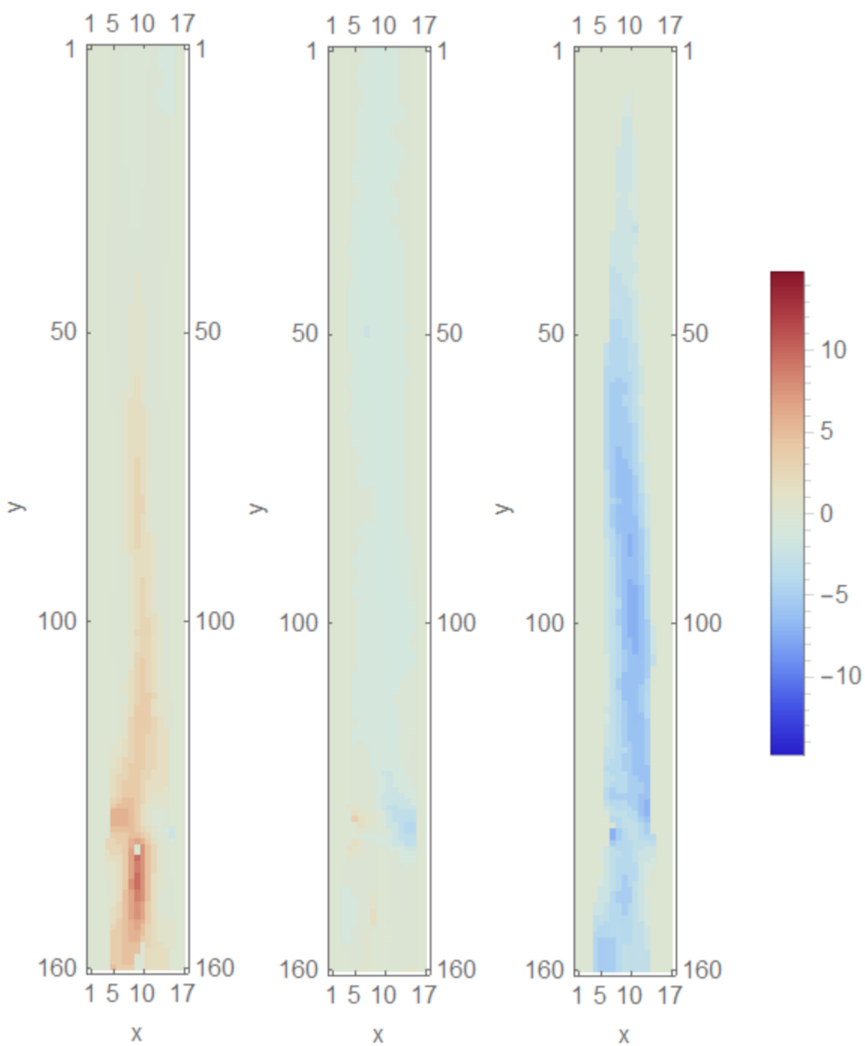




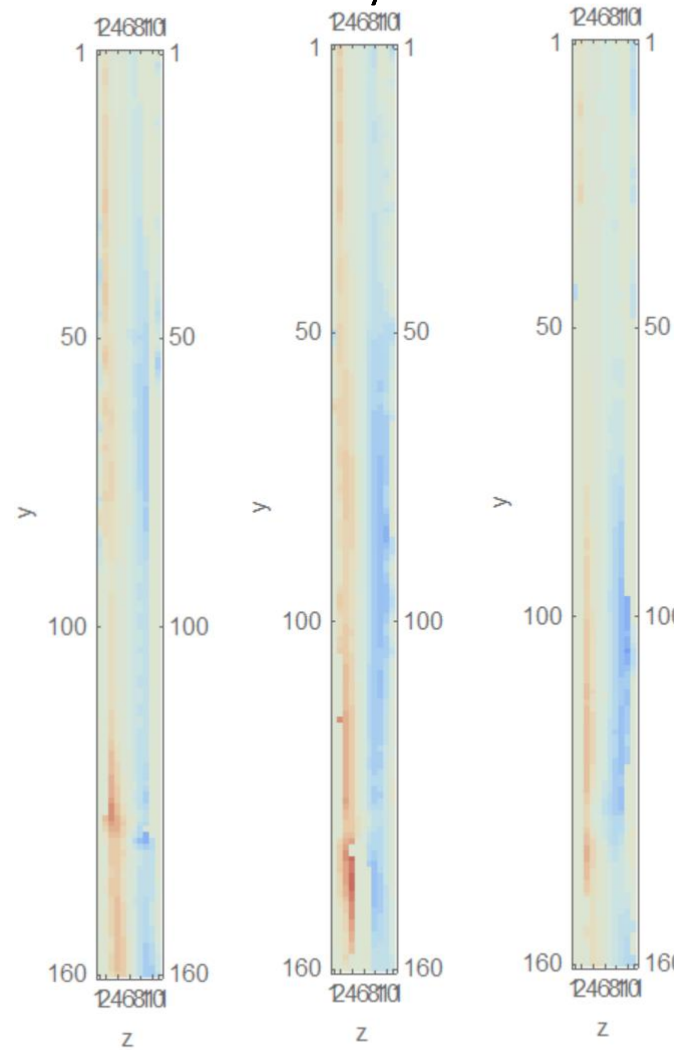
z = 3 z = 6 z = 9 x = 10

Transversal velocity (x component)



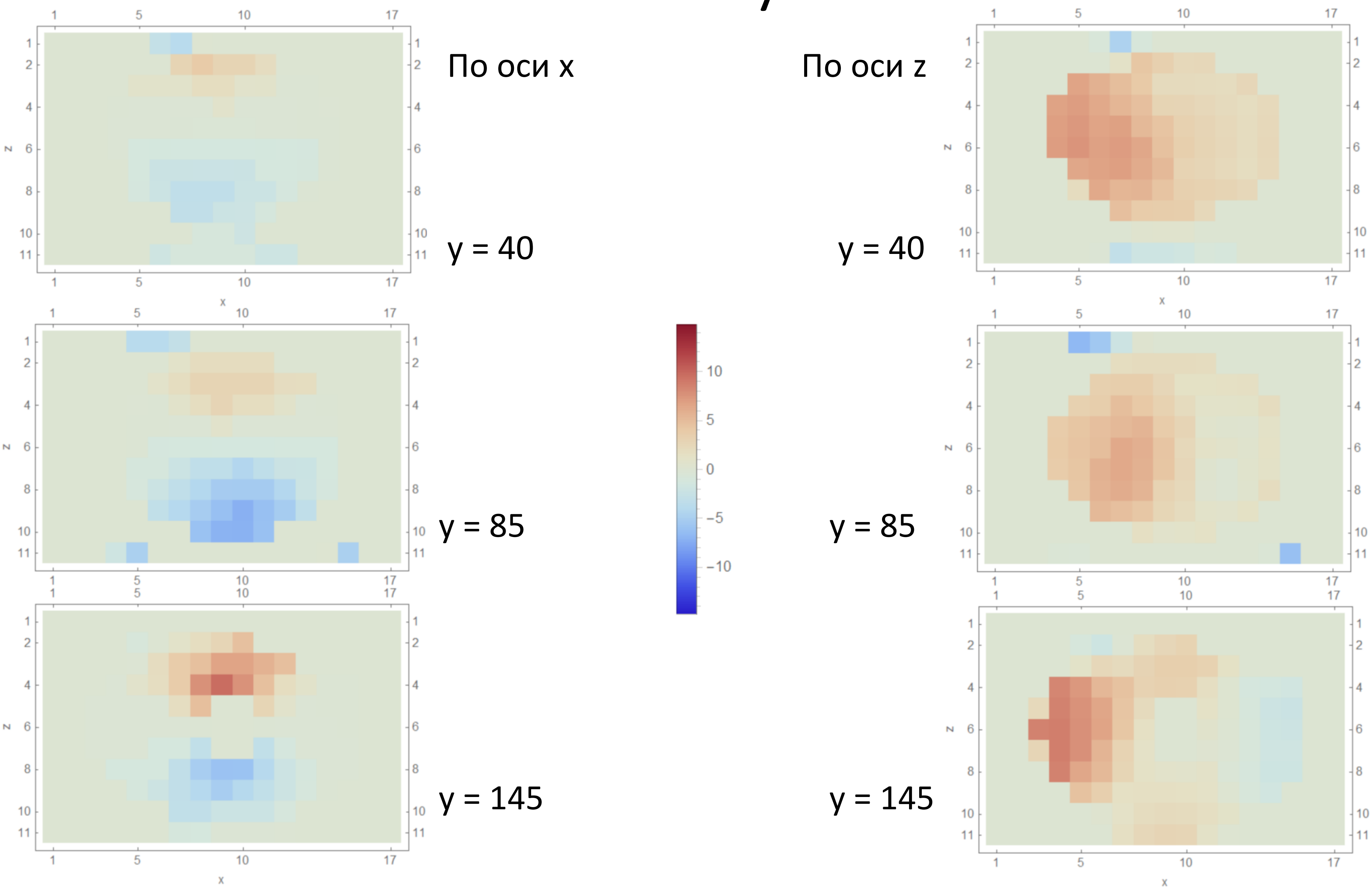


z = 4 z = 6 z = 9

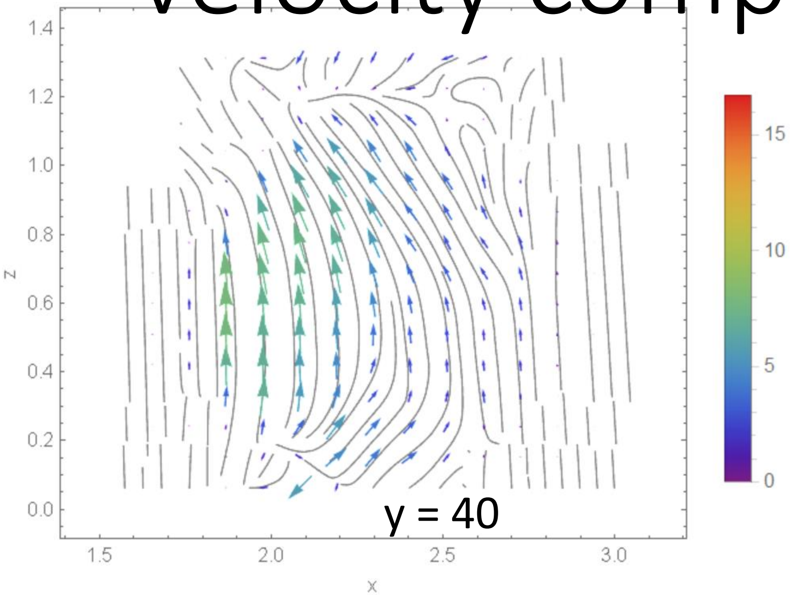


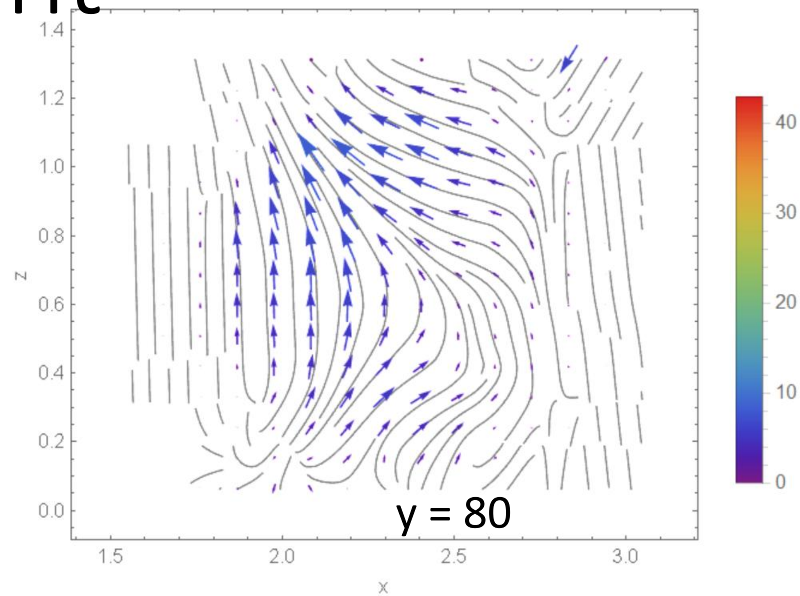
x = 7 x = 9 x = 12

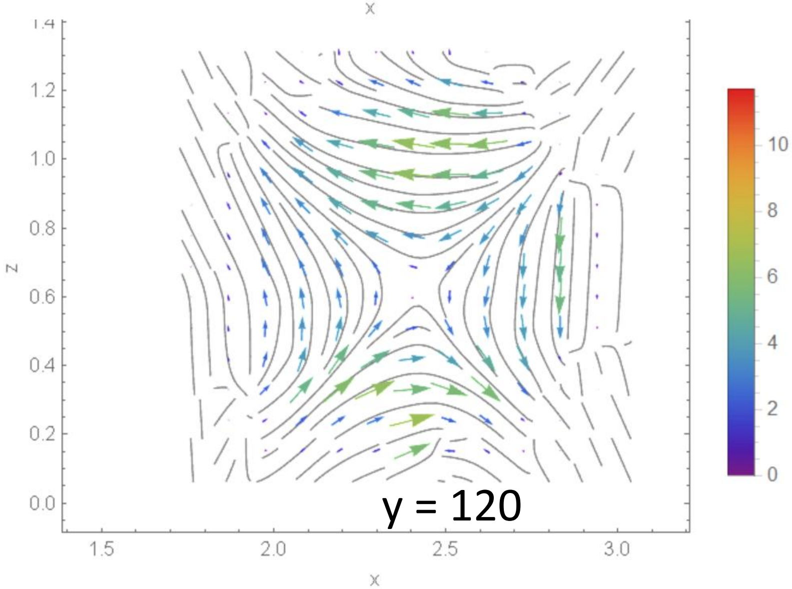
Transversal velocity

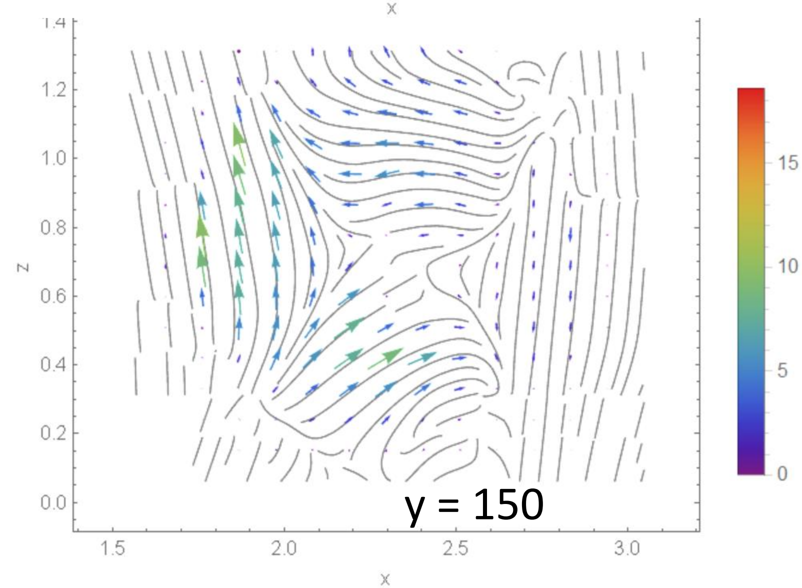


Streamlines for transversal velocity component



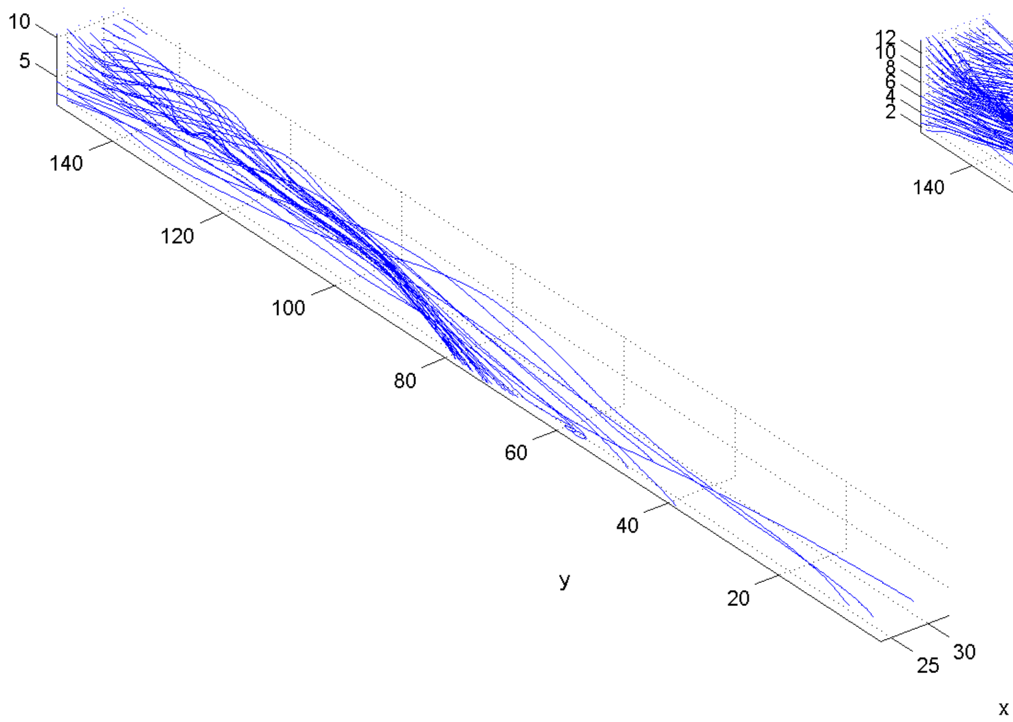




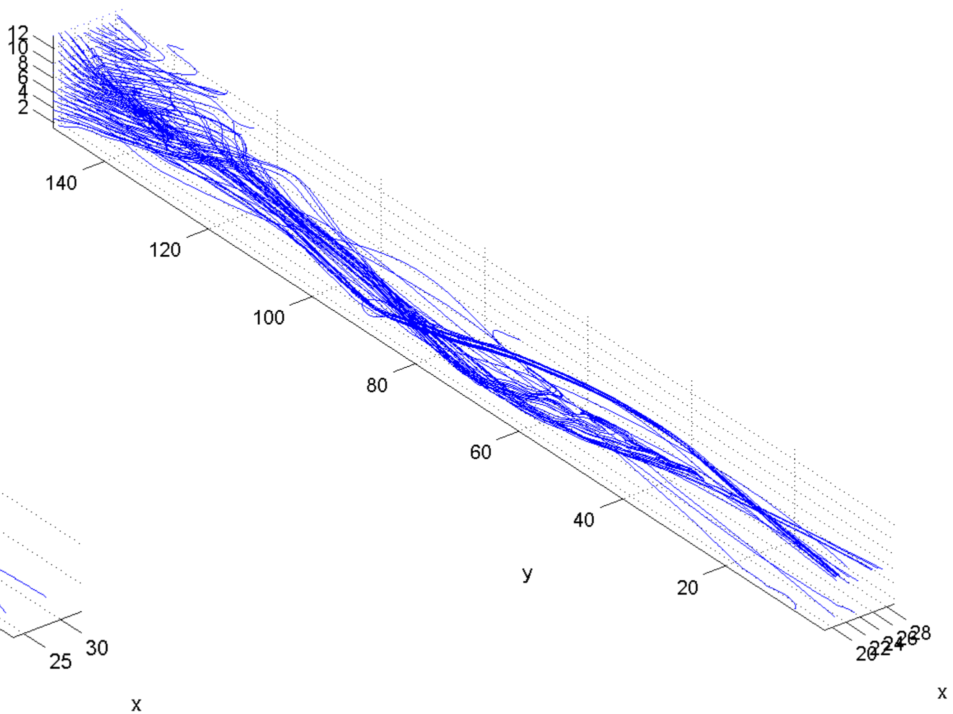


Streamlines

96x96x7



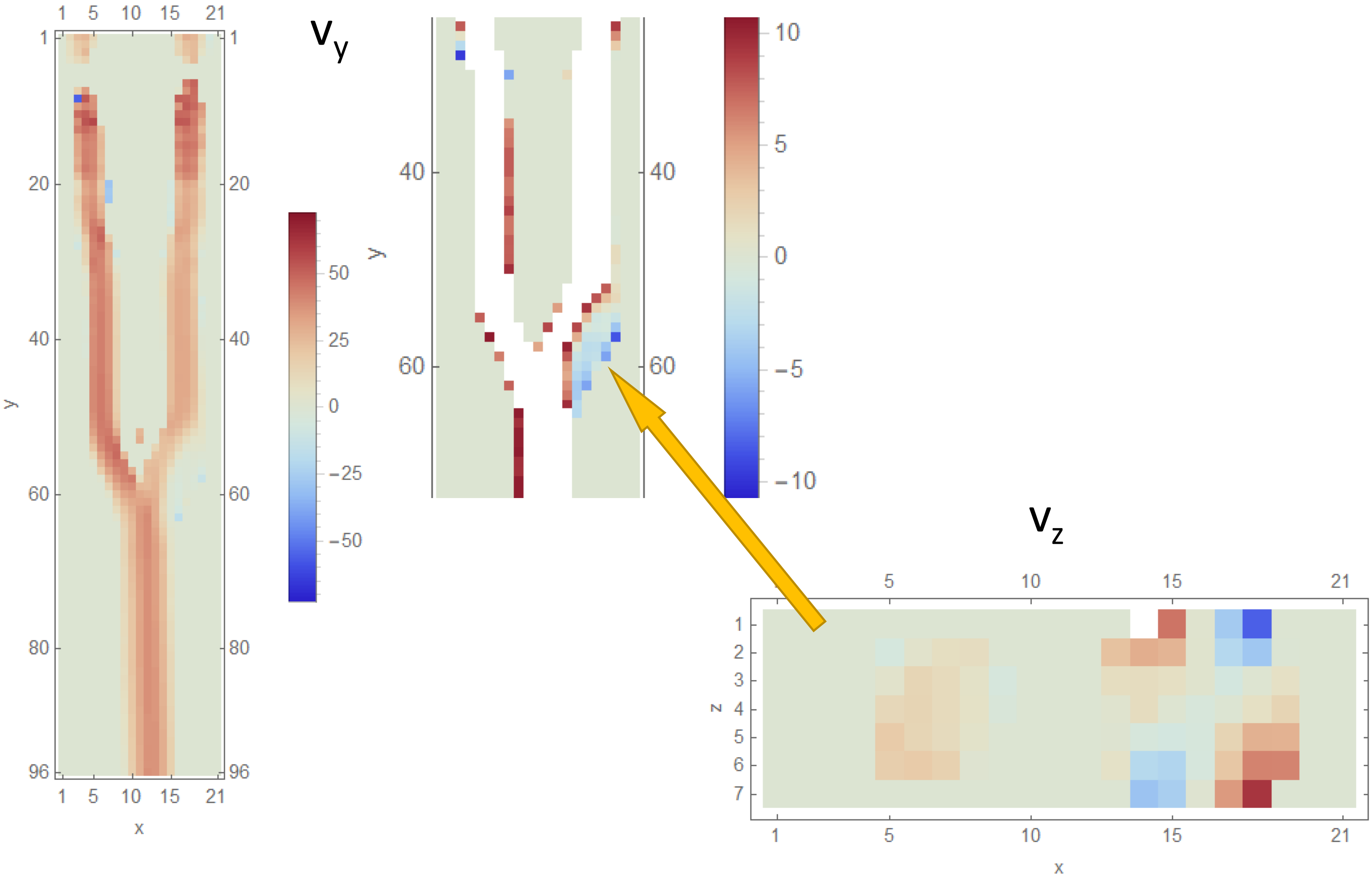
160×160×11



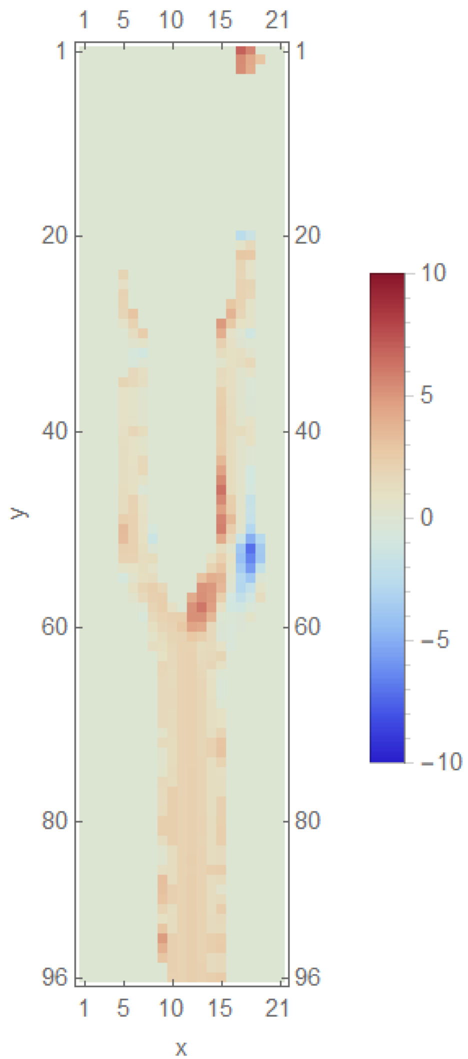
CCA bifurcation

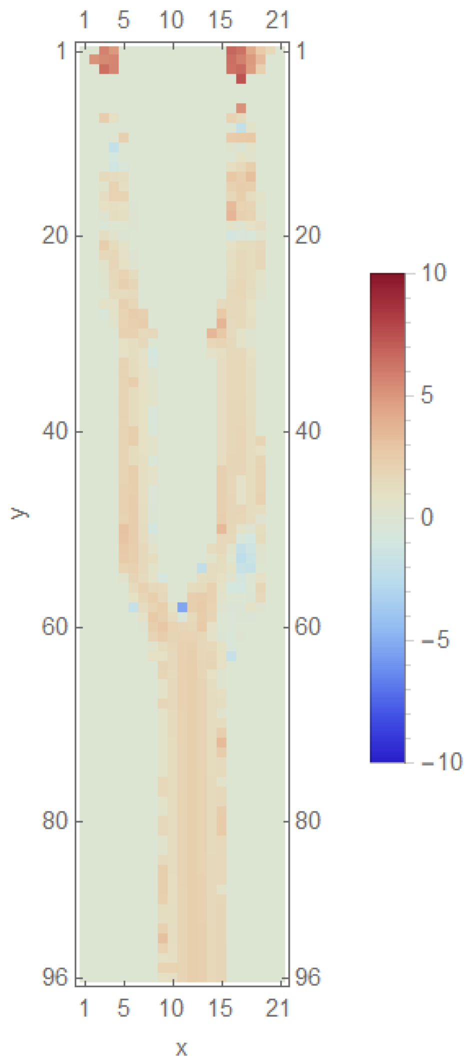
3D matrix	Time steps	Voxel, mm³	Domain, mm³	Files
96×96×7	20	1.56×1.56×1.5	150×150×10.5	4 × 280

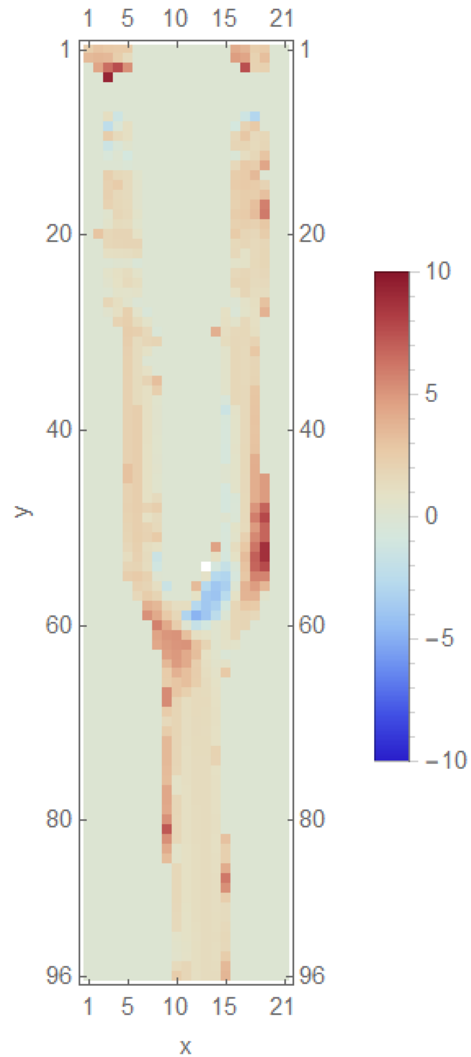
Velocity field



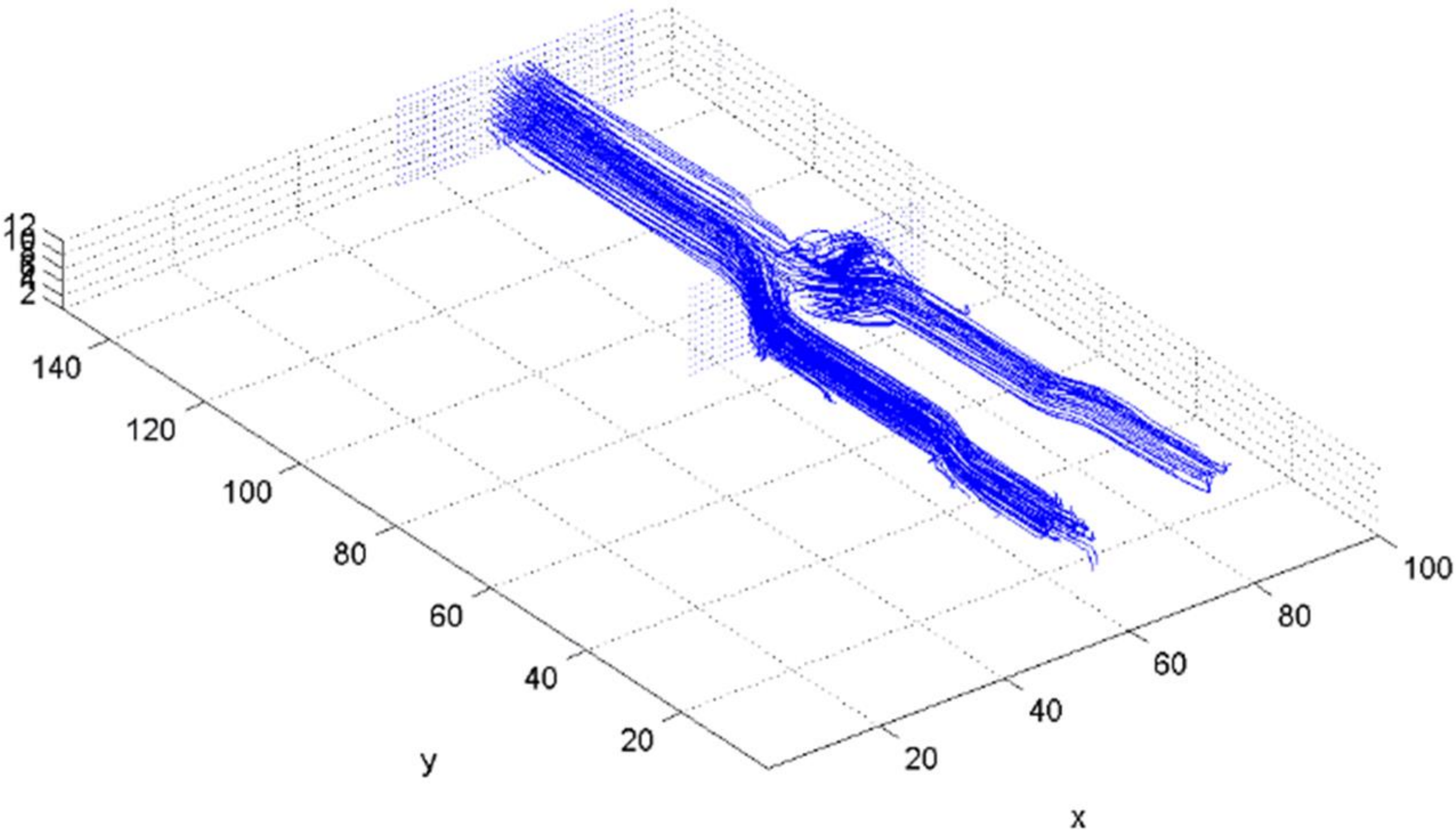
Velocity field: v_z







Streamlines

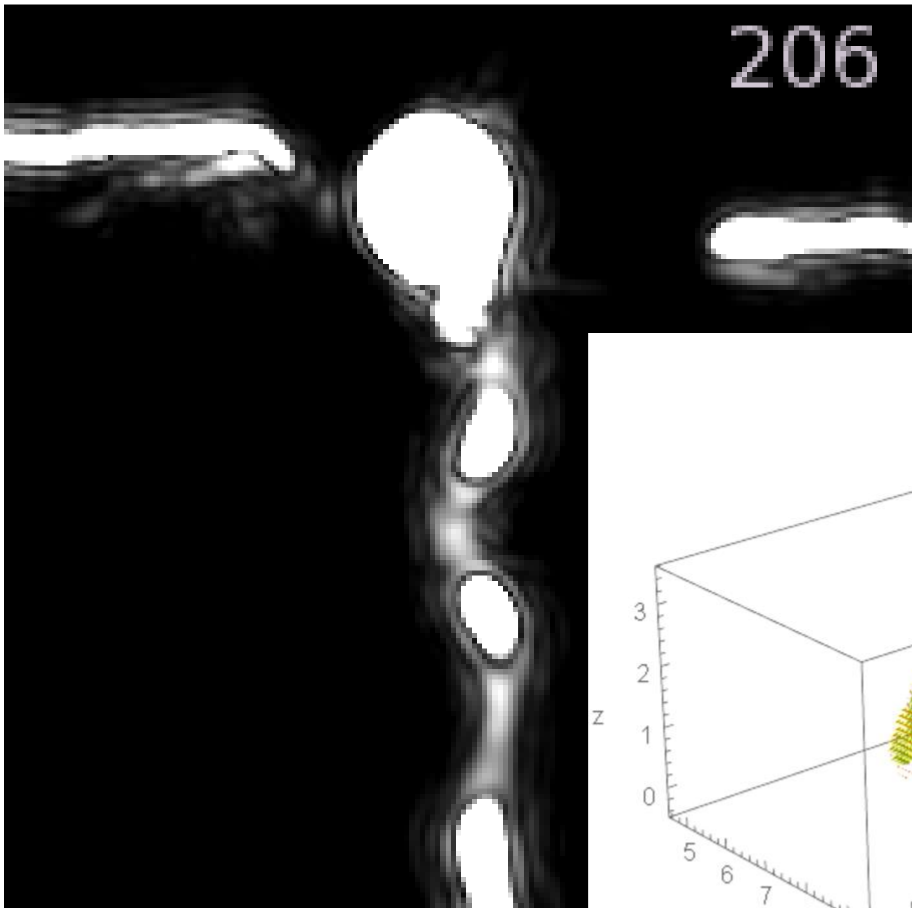


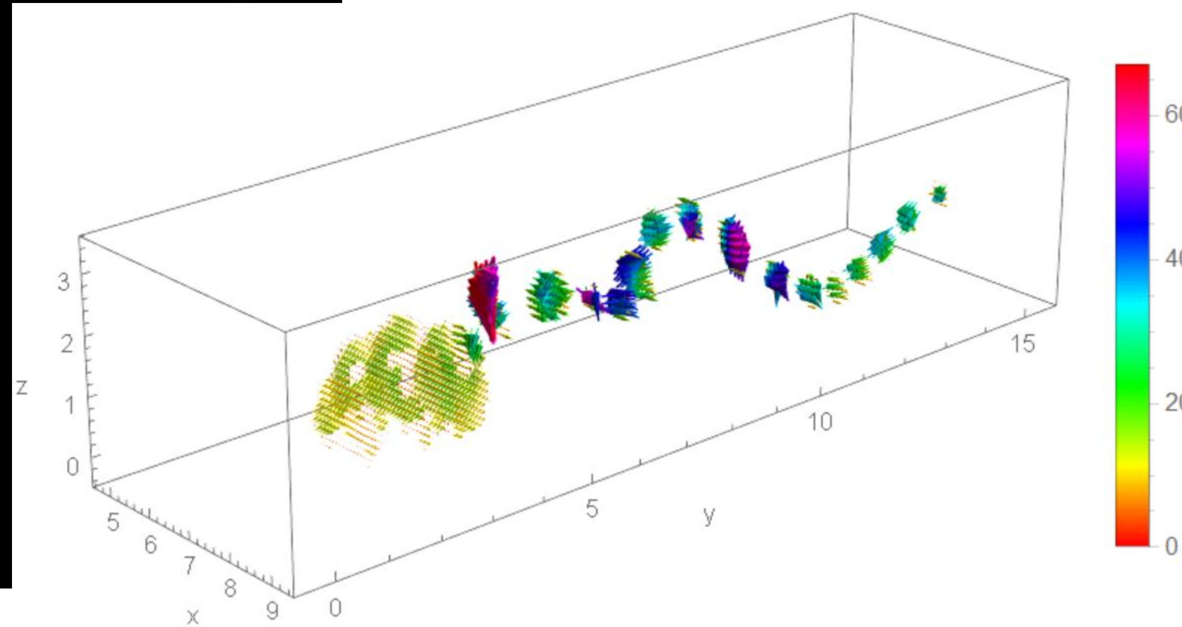
Aneurysm model

- Silicone model of cerebral blood vessels with aneurysm
- Flow rate: 12 ± 3 ml/s
- Frequency: 0,5 Hz

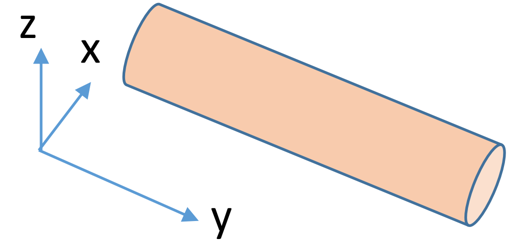
3D matrix	Time steps	Voxel, mm^3	Domain, mm^3	Files
176×176×25	20	0.86×0.86×1.25	150.6×150.6×31.25	4 × 1000

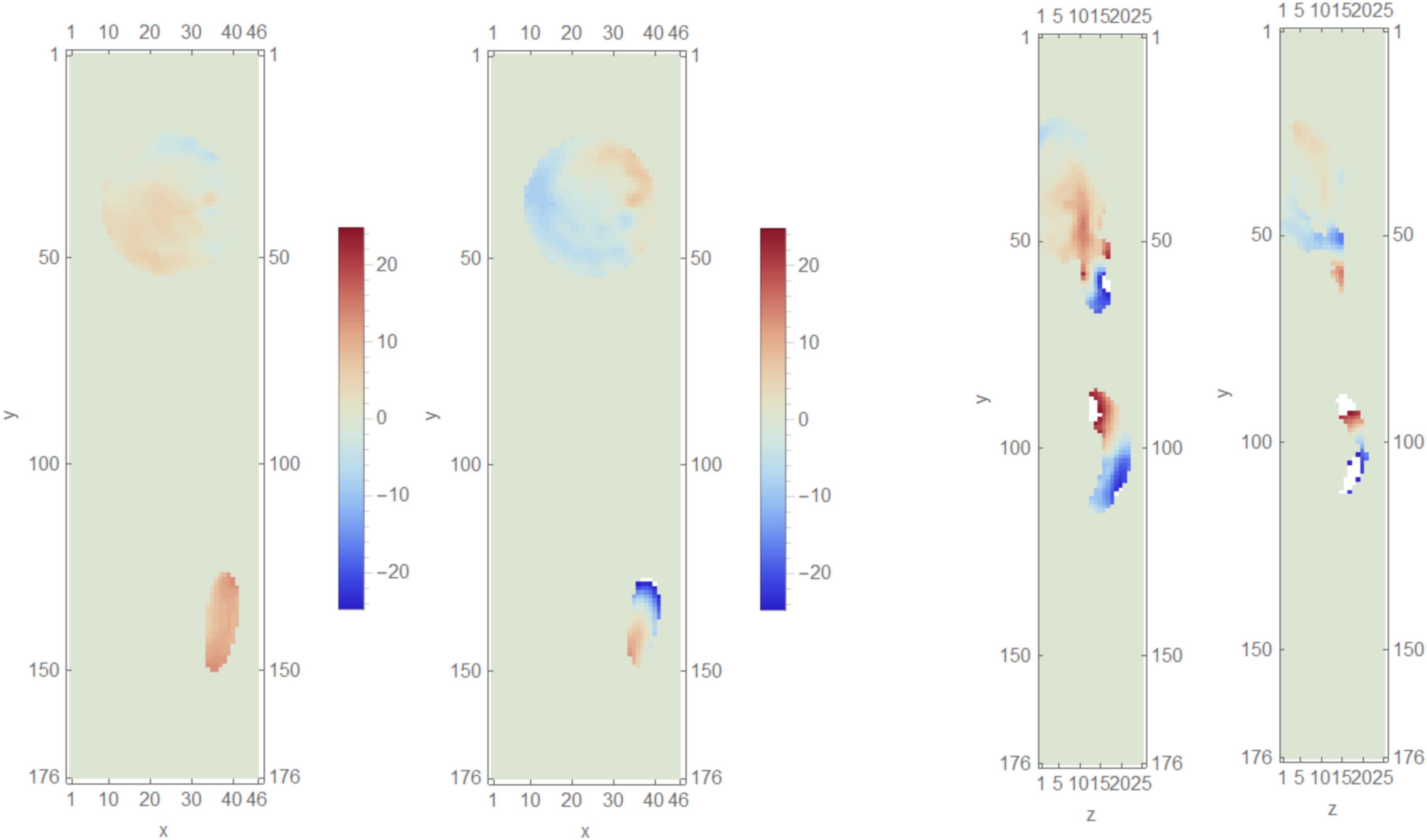
Matrix 176×176×25





Transversal velocity





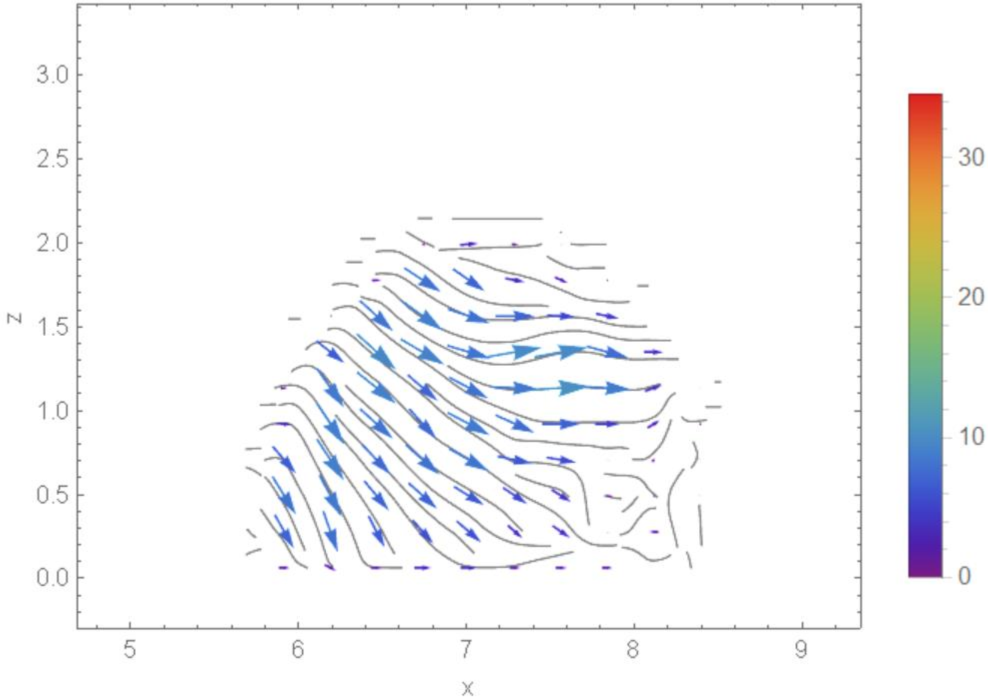
vx(z = 4)

vz(z = 4)

vx(x = 29)

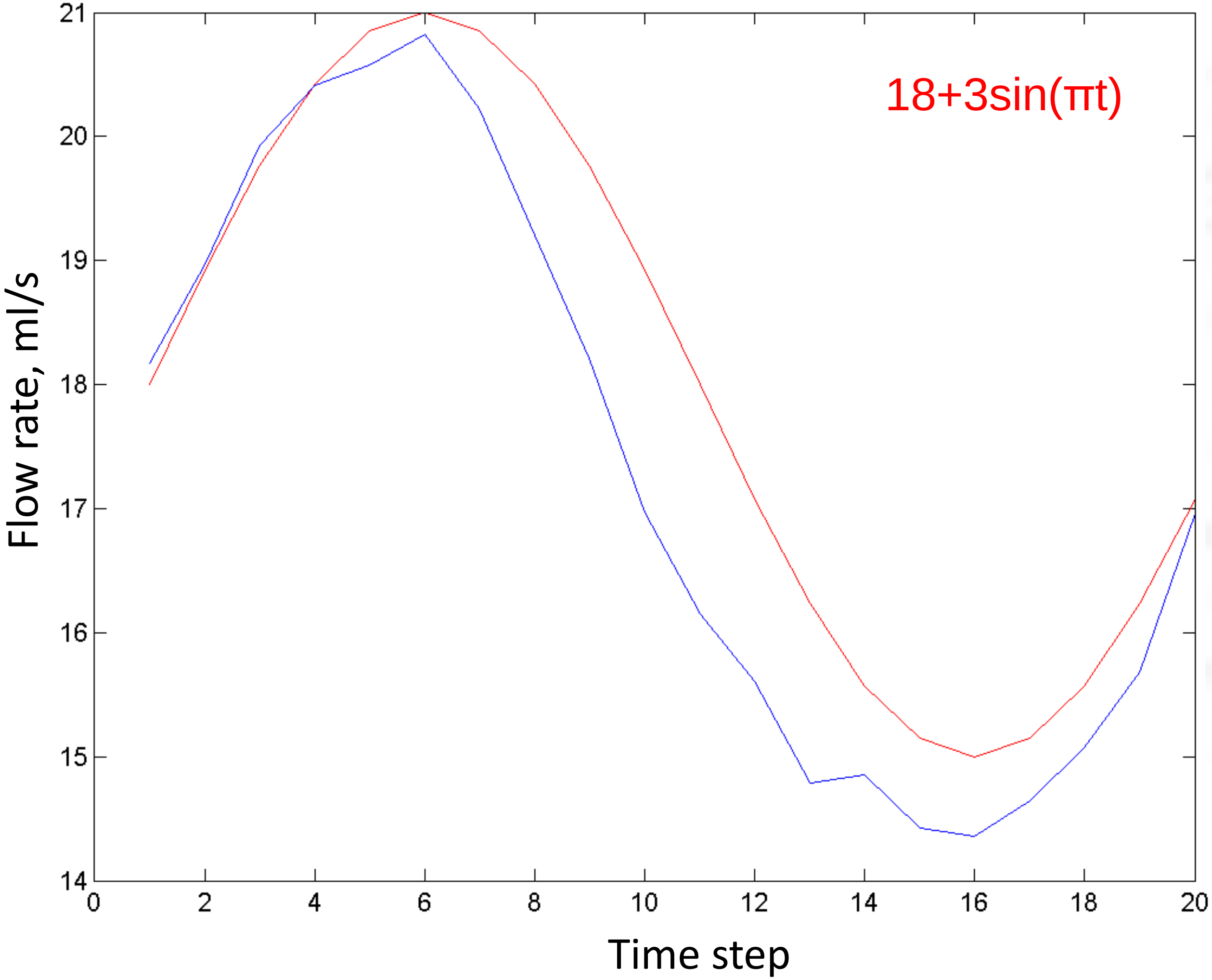
vz(x = 29)

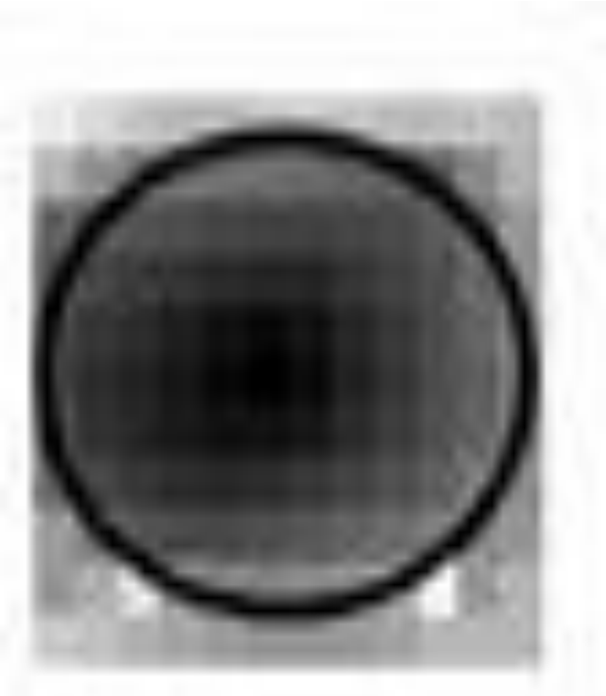
Streamlines for transversal velocity component



y = 40

Flow rate in tube





Tube cross-section

Conclusion

- Possibility to study swirling (helical) character of the flow with magnetic resonance imaging is shown.
- The scanning protocol is planned to be used in medical examinations for studying the flow structure in blood vessel, in particular, in cerebral arteries.
- This allows one to estimate not only volumetric flow rate and linear velocity but also secondary (rotational) flows.