# Gap vortex street formation in the bare rod bundles

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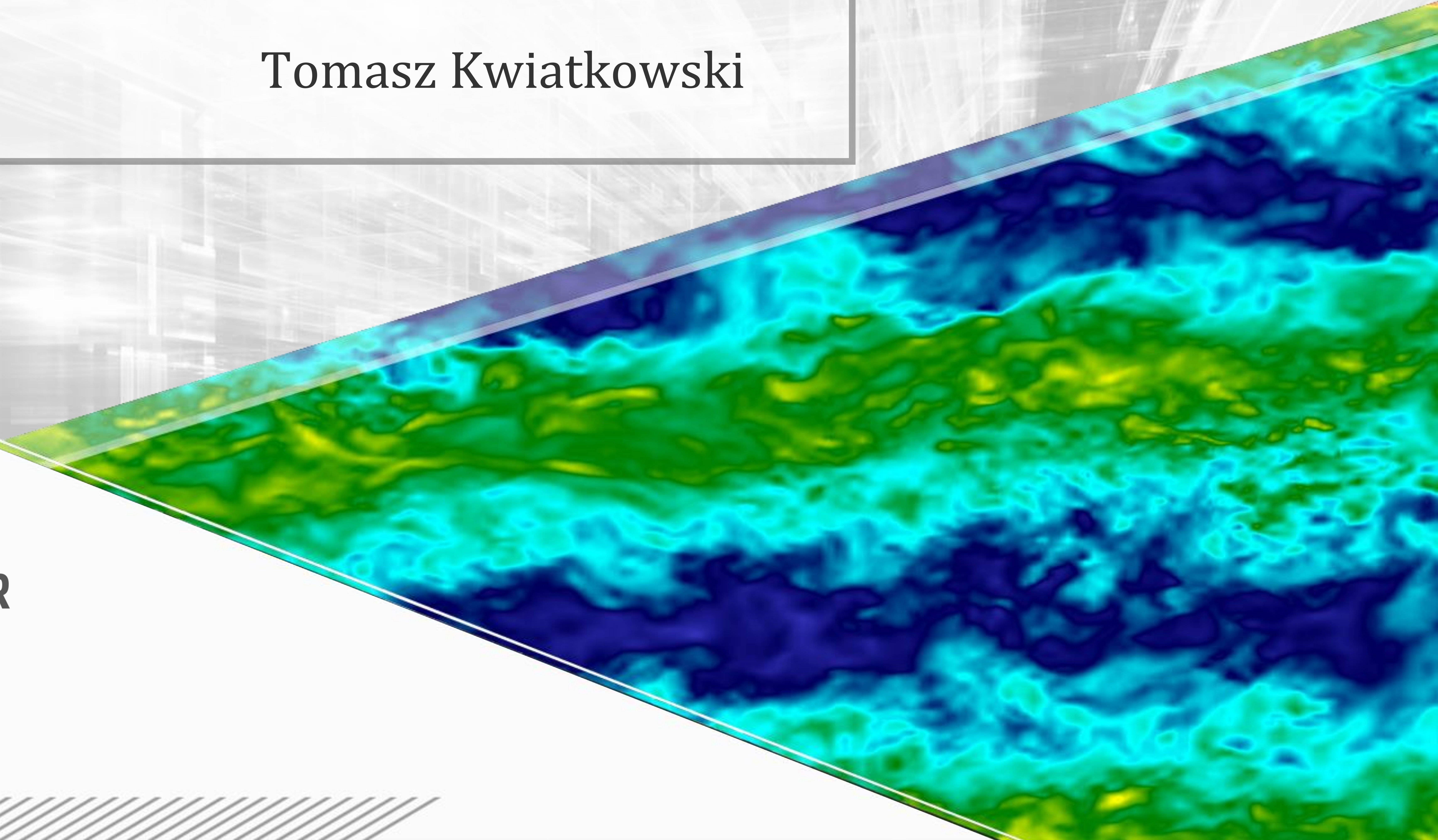
ŚWIERK



# Long-term motivation

- In December 2016, a research project has been established between NCBJ & NRG (the Netherlands)

- In the frame of this agreement, two reference databases (DNS) were planned to be generated for different reactor safety-related topics:
  - Pressurized thermal shock (PTS)
  - Sub-channel of a bare rod bundle (Hooper case)

- The obtained results will yield in an extensive validation database for flow and heat transfer representing different reactor coolants

- Merit leading – dr Afaque Shams

# Main goals of current research

- Unsteady Reynolds Averaged Navier-Stokes (URANS) methodology is used to reproduce the **occurrence of the gap vortex street** in a square bare rod bundle configuration, considering three different criteria:

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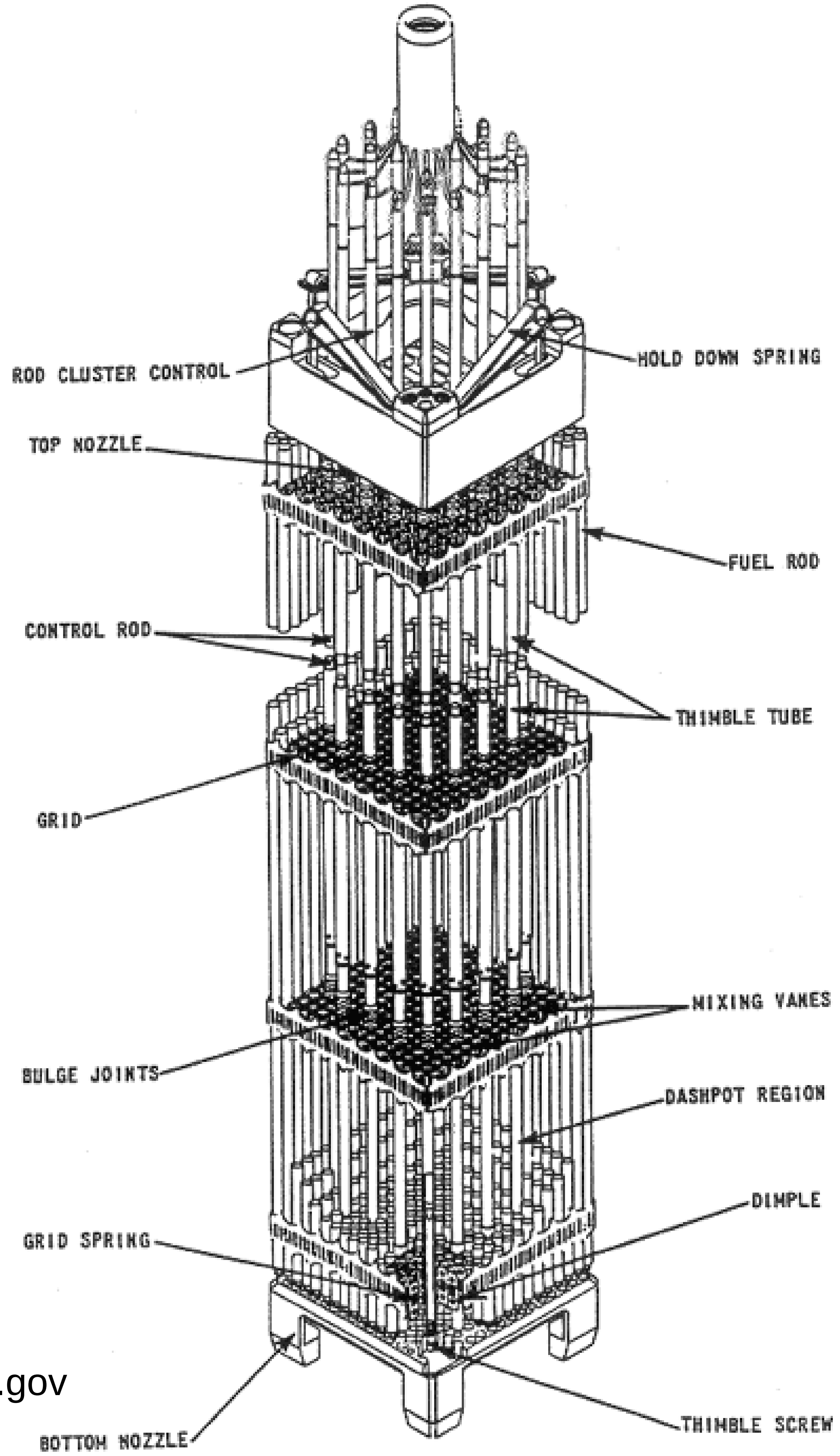
- Unsteady Reynolds Averaged Navier-Stokes (URANS) methodology is used to reproduce the **occurrence of the gap vortex street** in a square bare rod bundle configuration, considering three different criteria:
  - influence of the cross-section size domain
  - formation of the gap instability in the laminar flow regime
  - influence of the P/D ratio

# Terminology

- Bare rod bundle – simplified geometry of a real fuel assembly (without spacer grids, etc.)




Source: www.nrc.gov

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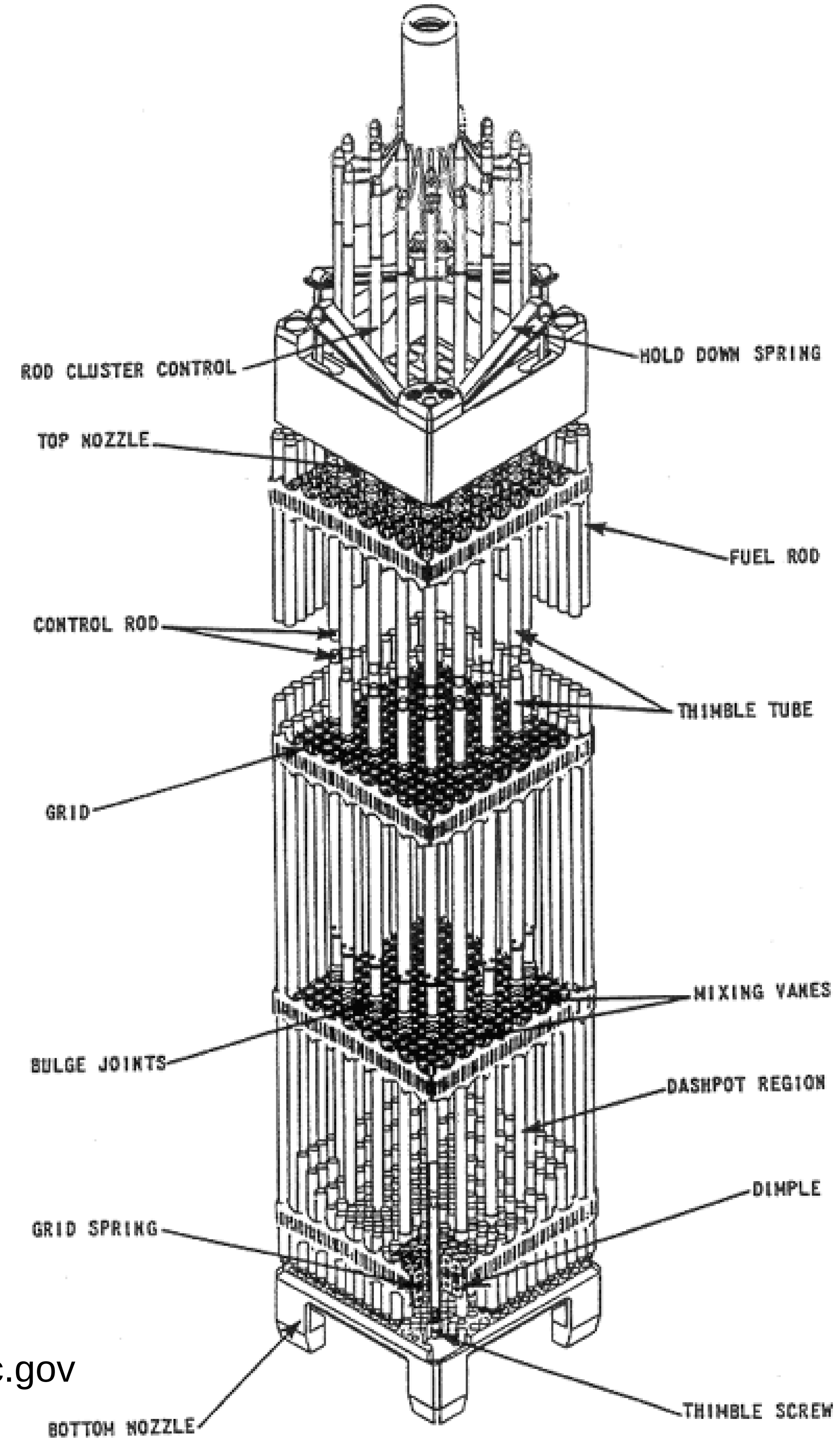


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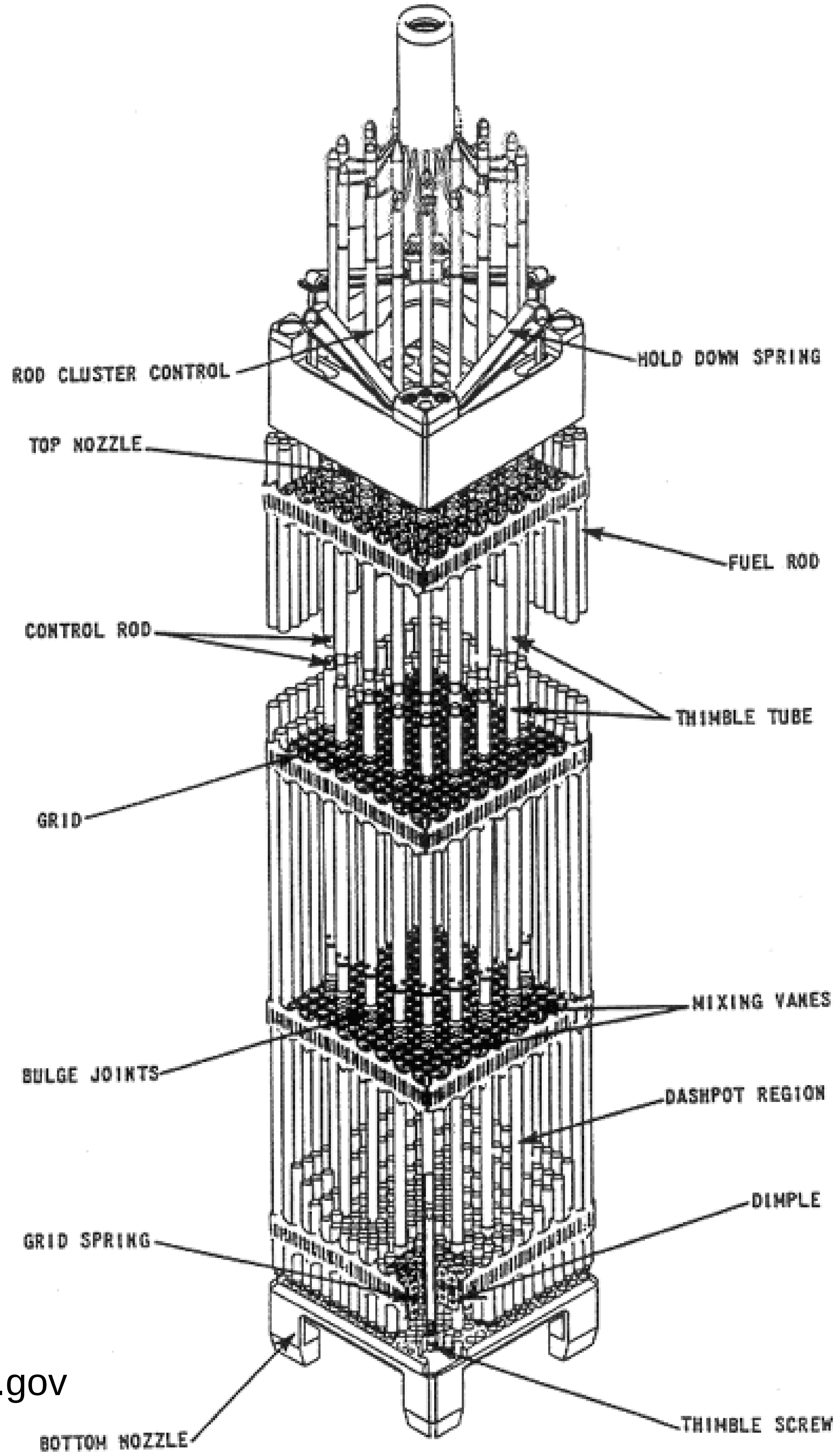


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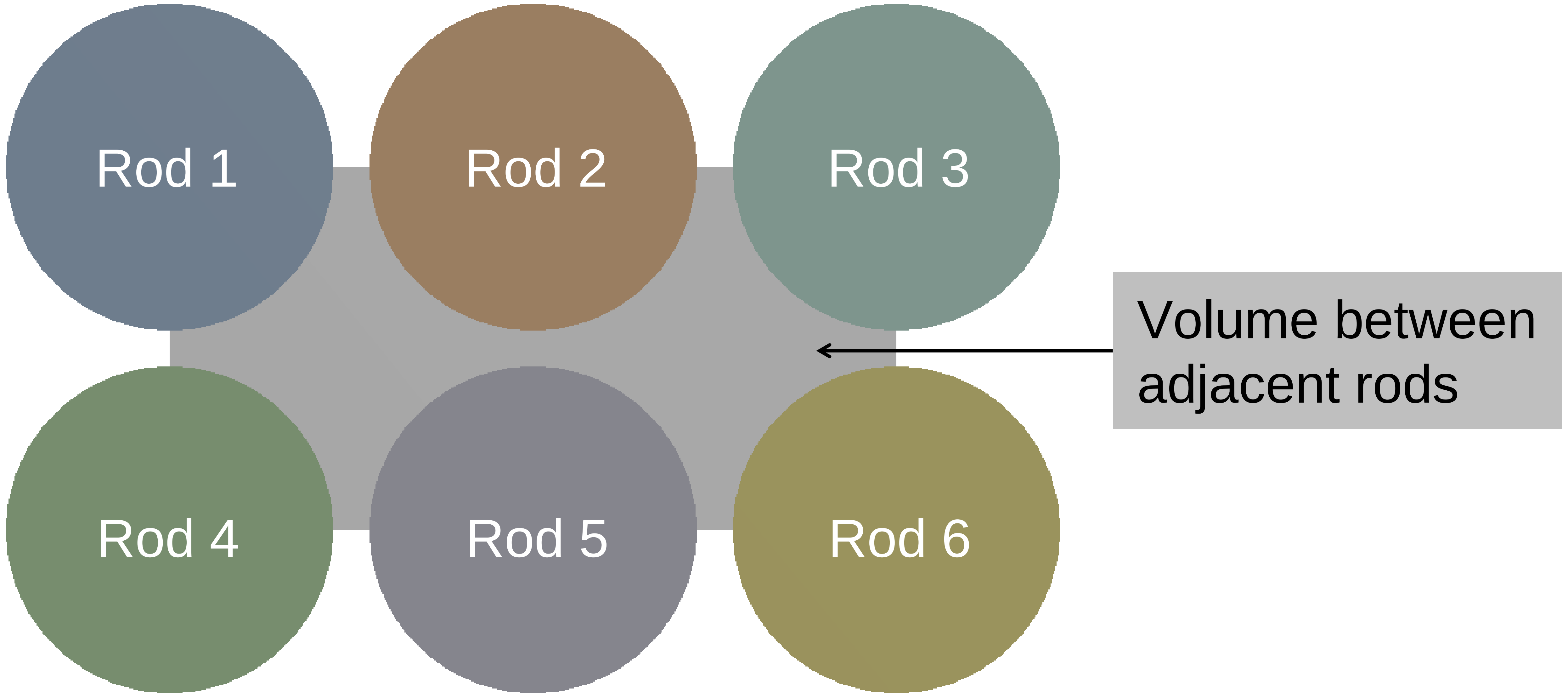
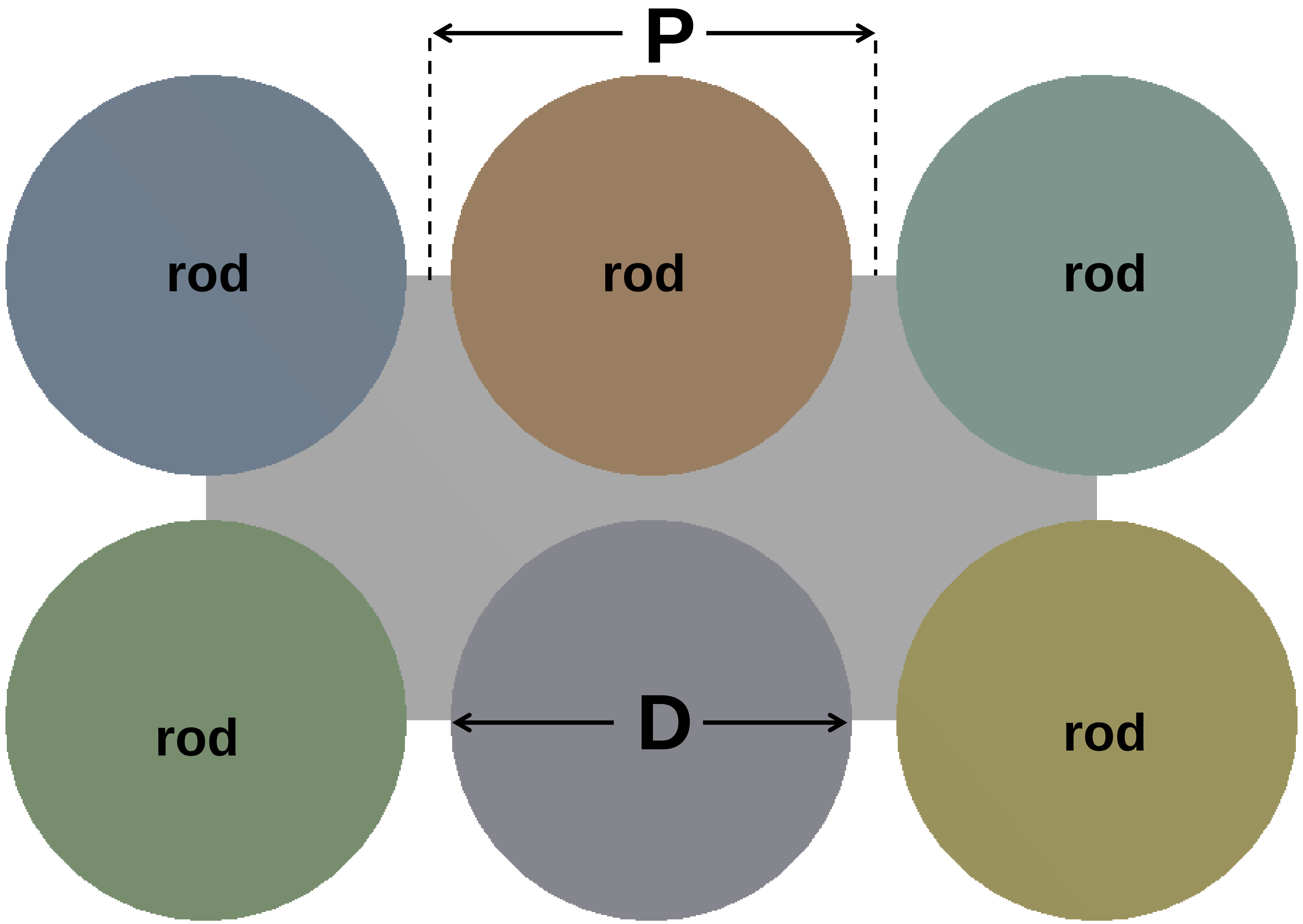


# Terminology

- P/D ratio – pitch-to-diameter ratio, geometric parameter used in nuclear fuel bundles. Indicate how tightly rods are packed in the fuel assembly.



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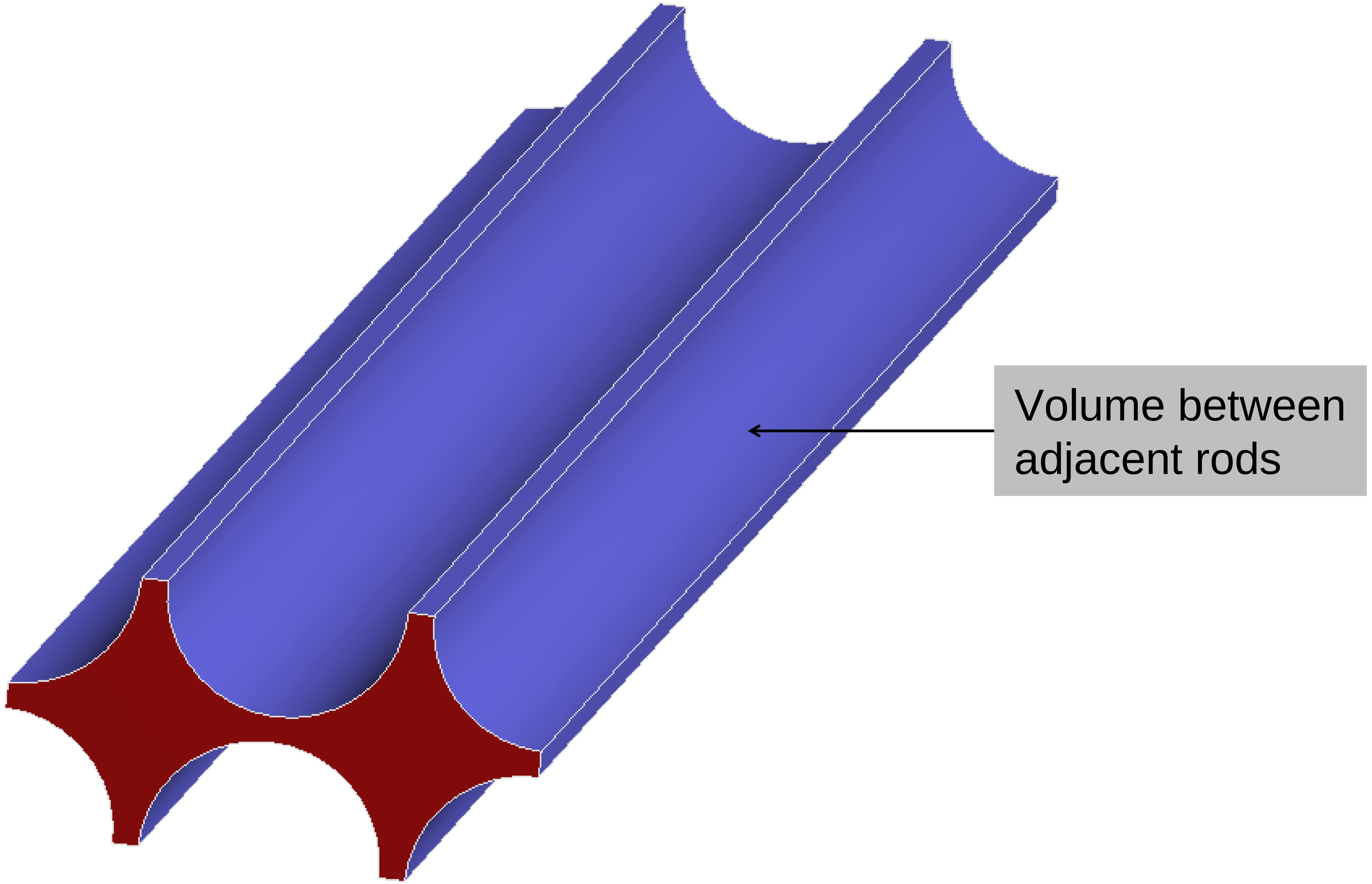
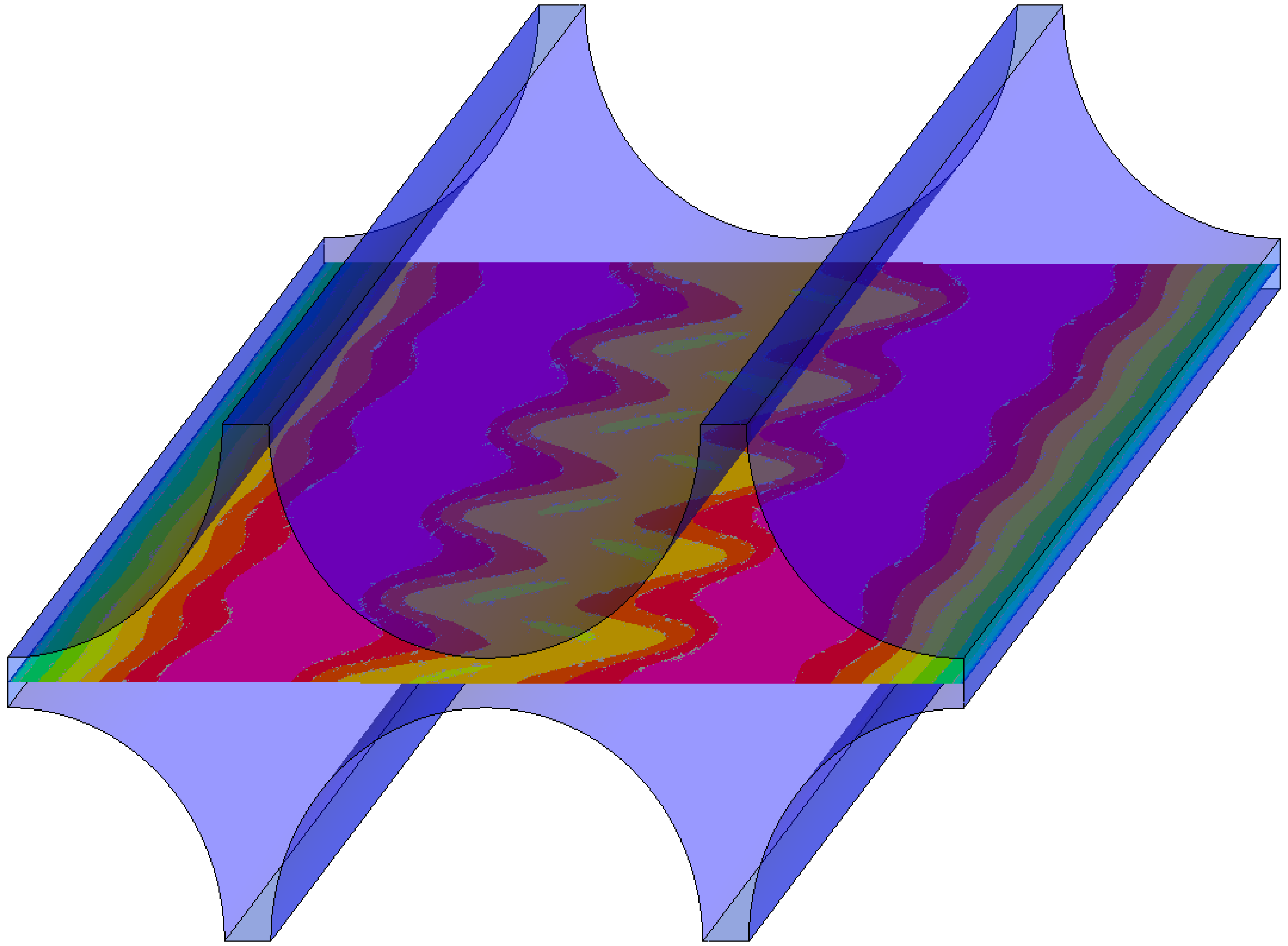
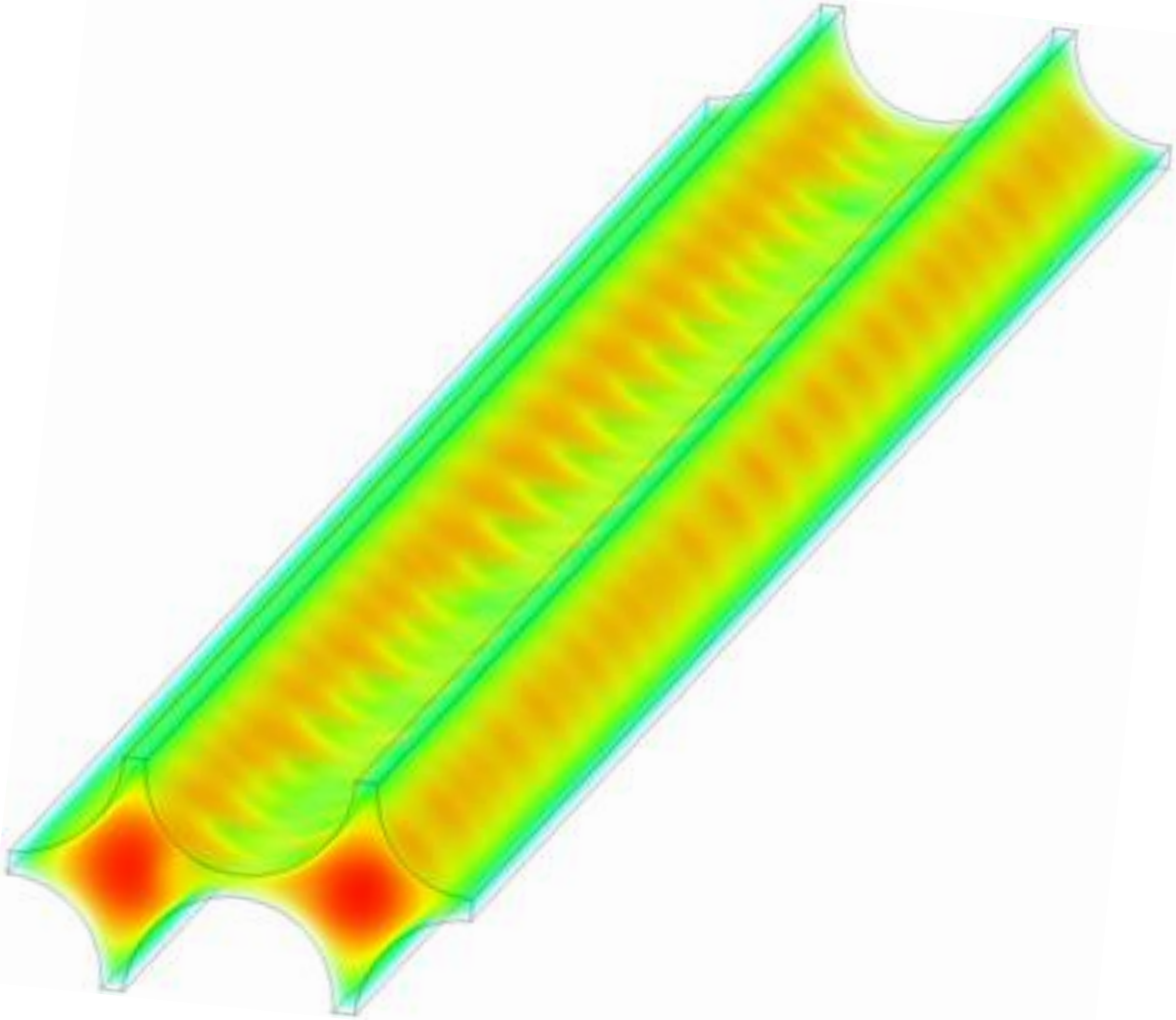


# Terminology

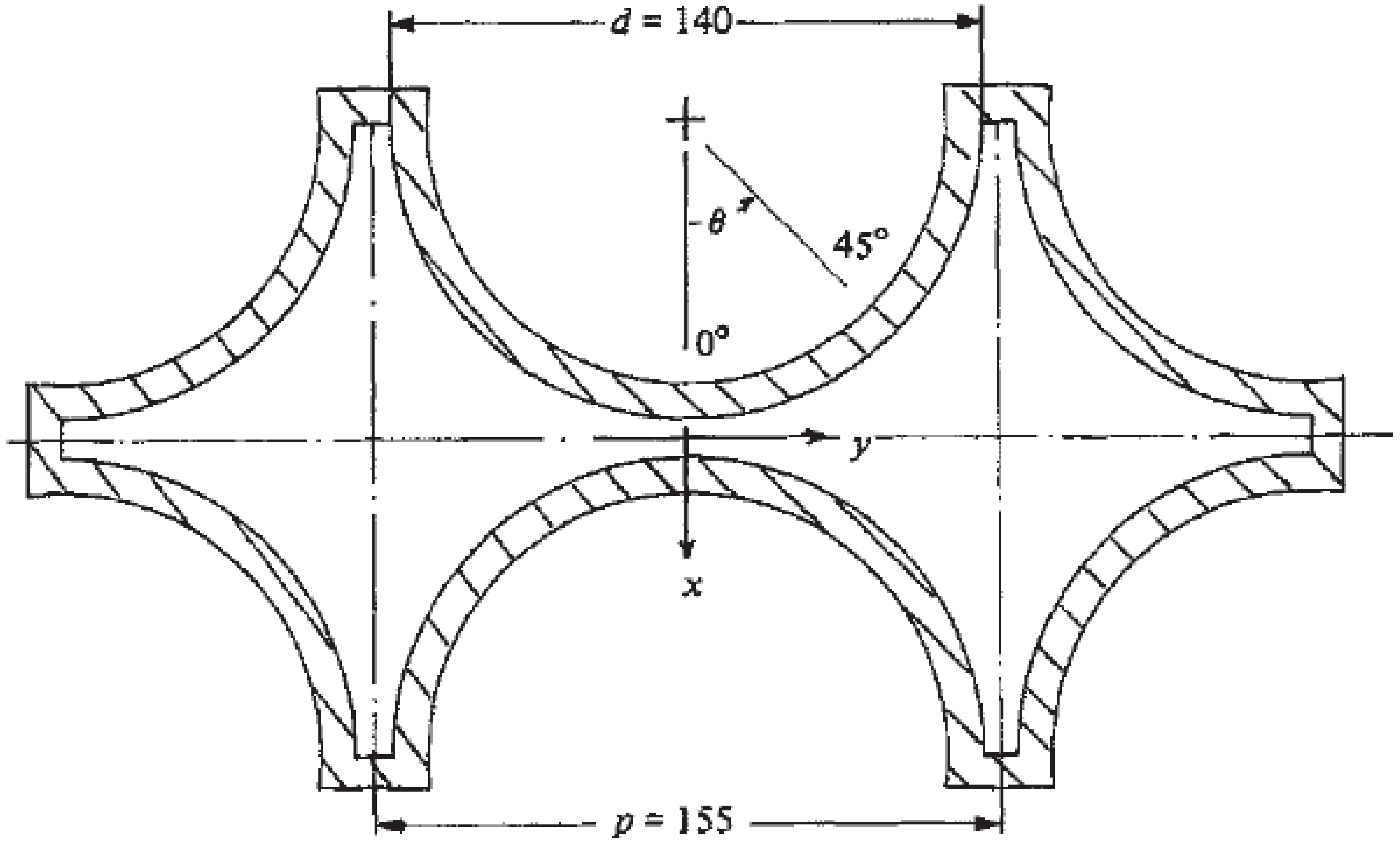
- Gap vortex street – large-scale motions across an individual gap. Very often called as *flow pulsations*, nevertheless, pulsations are only a symptom of the condition of the flow and this term provides no physical insight into the overall structure of the velocity field. The pulsations are the result of the interactions between sequences of counter-rotating vortices on the either side of the gap.





# Rod bundle case – Hooper case

## Experimental set-up



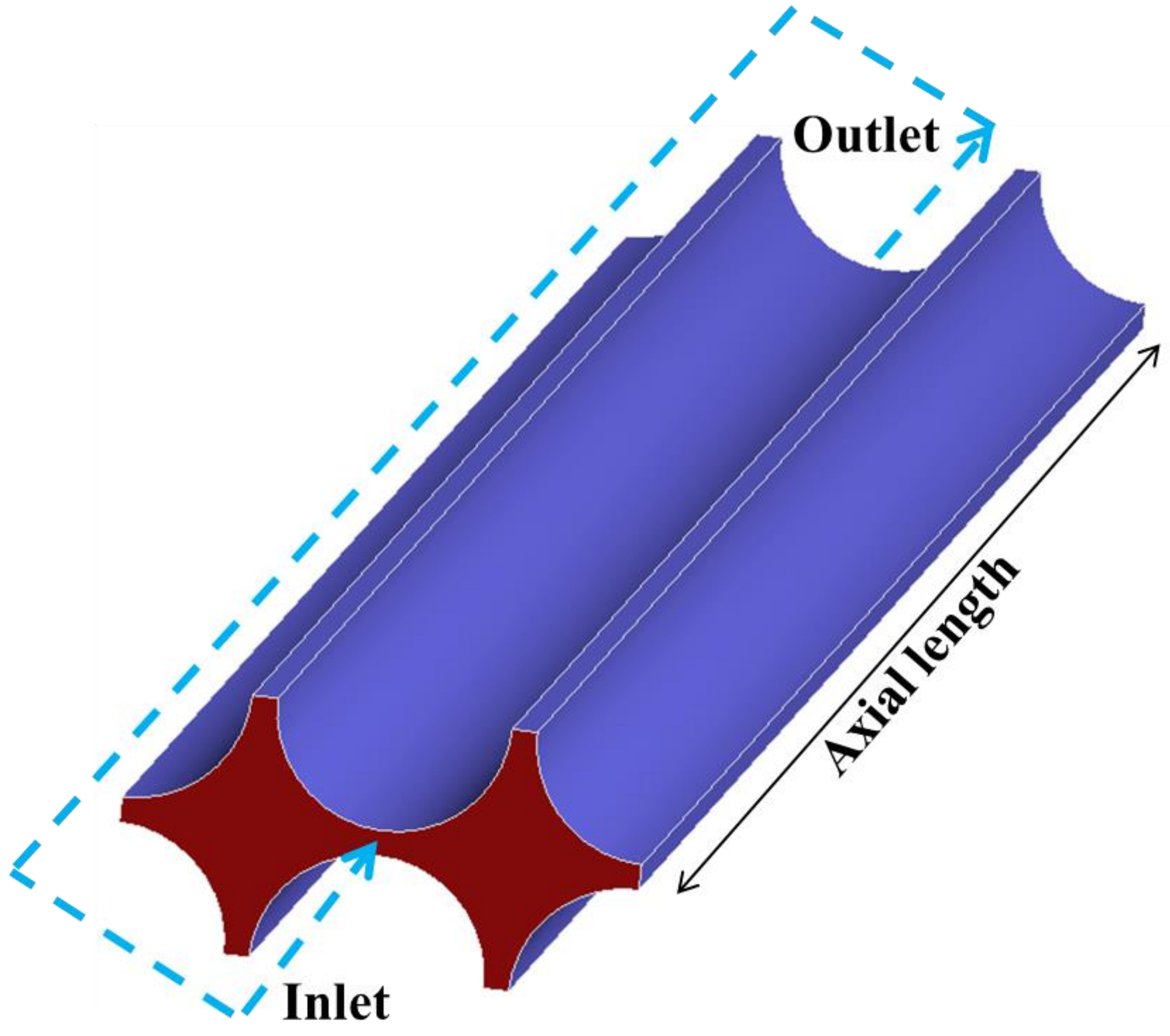

Hooper J. D., Rehme K.,
*Large-scale structural effects in developed turbulent flow through closely-spaced rod arrays*,
J. Fluid Mech. (1984), vol. 145, pp 305-337

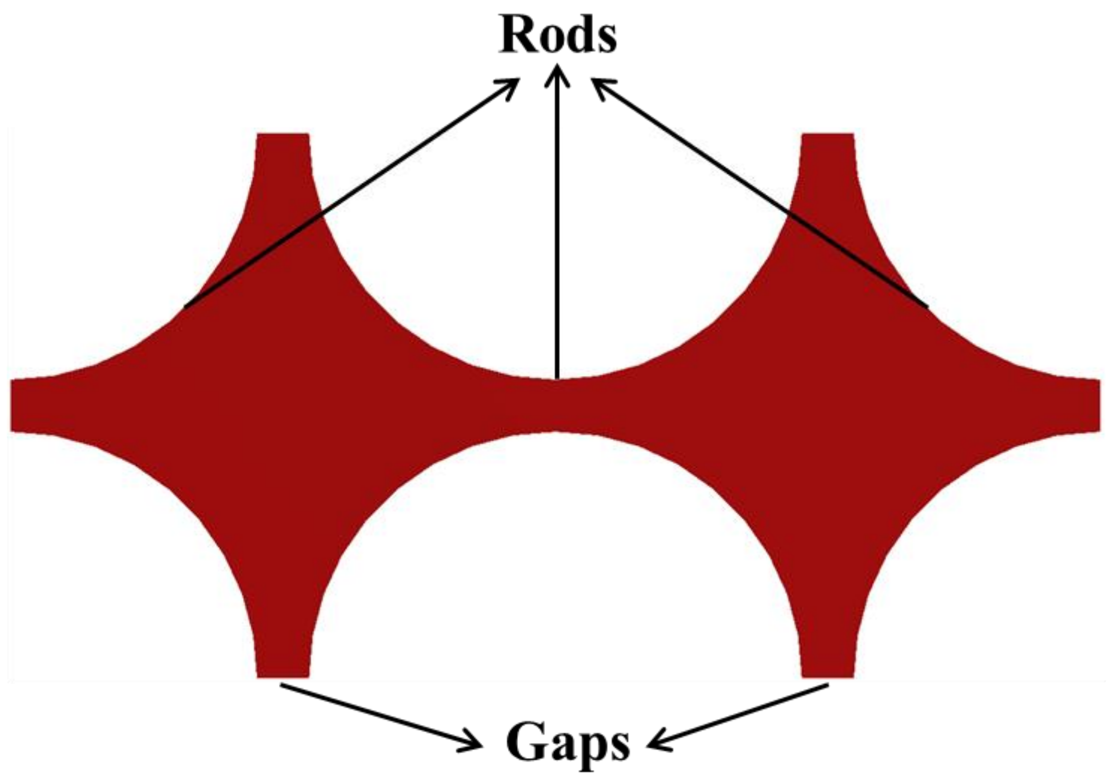
## Key parameters

- Six rods lattice
- Square configuration
- Working fluid: air at normal conditions
- d = 14 cm
- p = 15.5 cm
- p/d = 1.107
- L = 9.14 m
- Re = 49 000
- $\bar{v} = 10.3\ \frac{m}{s}$

# Rod bundle case – Hooper case

## Numerical domain




## Key parameters

- Six rods lattice
- Square configuration
- d = 14 cm
- p = 15.5 cm
- p/d = 1.107
- L = 9.14 m
- Re = 49 000
- Boundary conditions:
  - $\dot{m} = 0.213\ \frac{kg}{s}$
  - Periodic in- and outlet
  - Rods and gaps surfaces: no-slip wall

# Occurrence of flow pulsation

- Influence of the cross-section size domain

- Laminar flow regime

- Influence of the rod gap width

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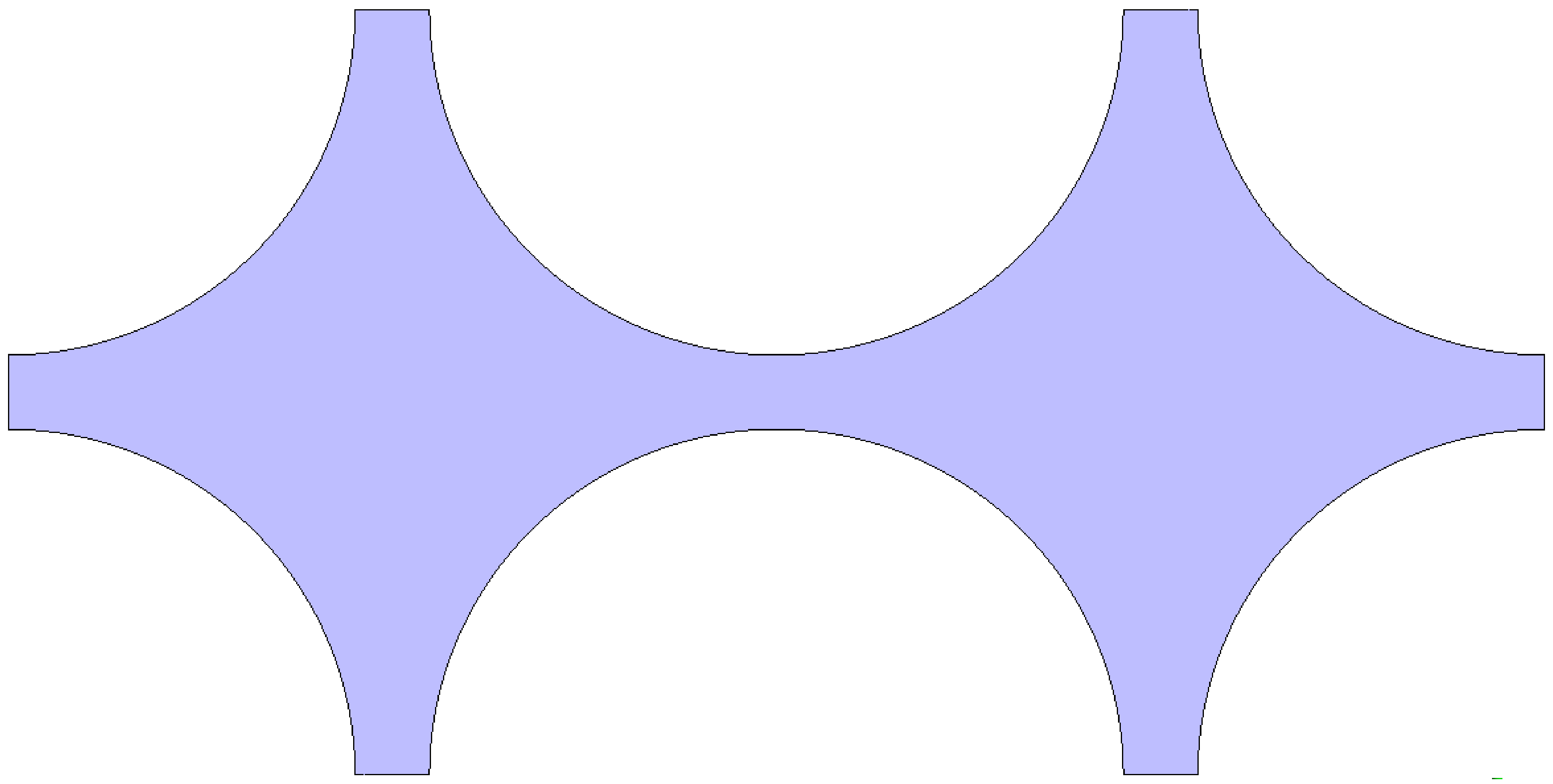
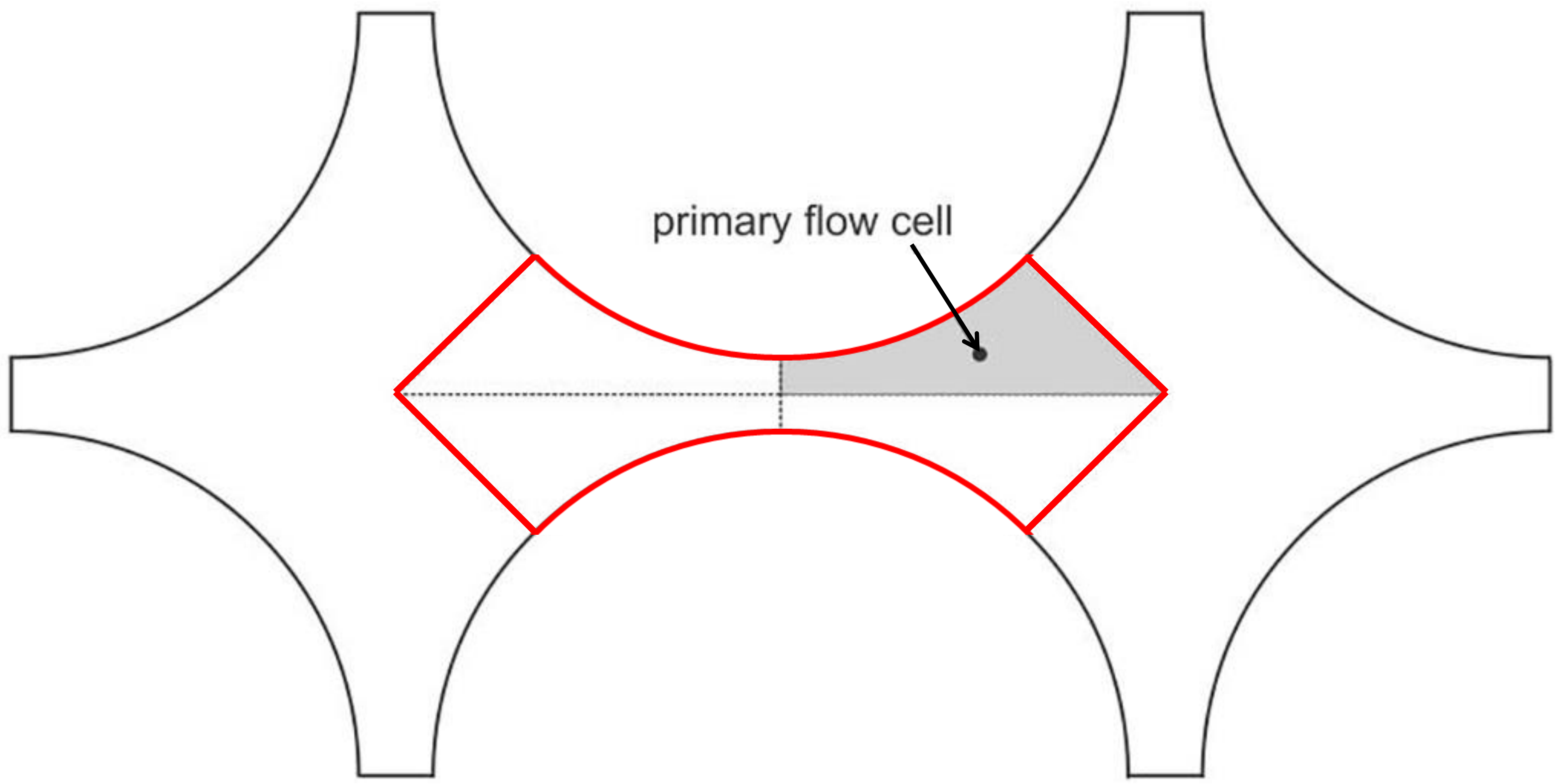
# Computational domain size

## Full cross-section domain (F)



## Cross-sectional domain (CS)




*A. SHAMS and T. KWIATKOWSKI, "**Towards the Direct Numerical Simulation of a closely-spaced bare rod bundle**," Ann. Nucl. Energy 121, 146, Elsevier Ltd (2018); https://doi.org/10.1016/j.anucene.2018.07.022

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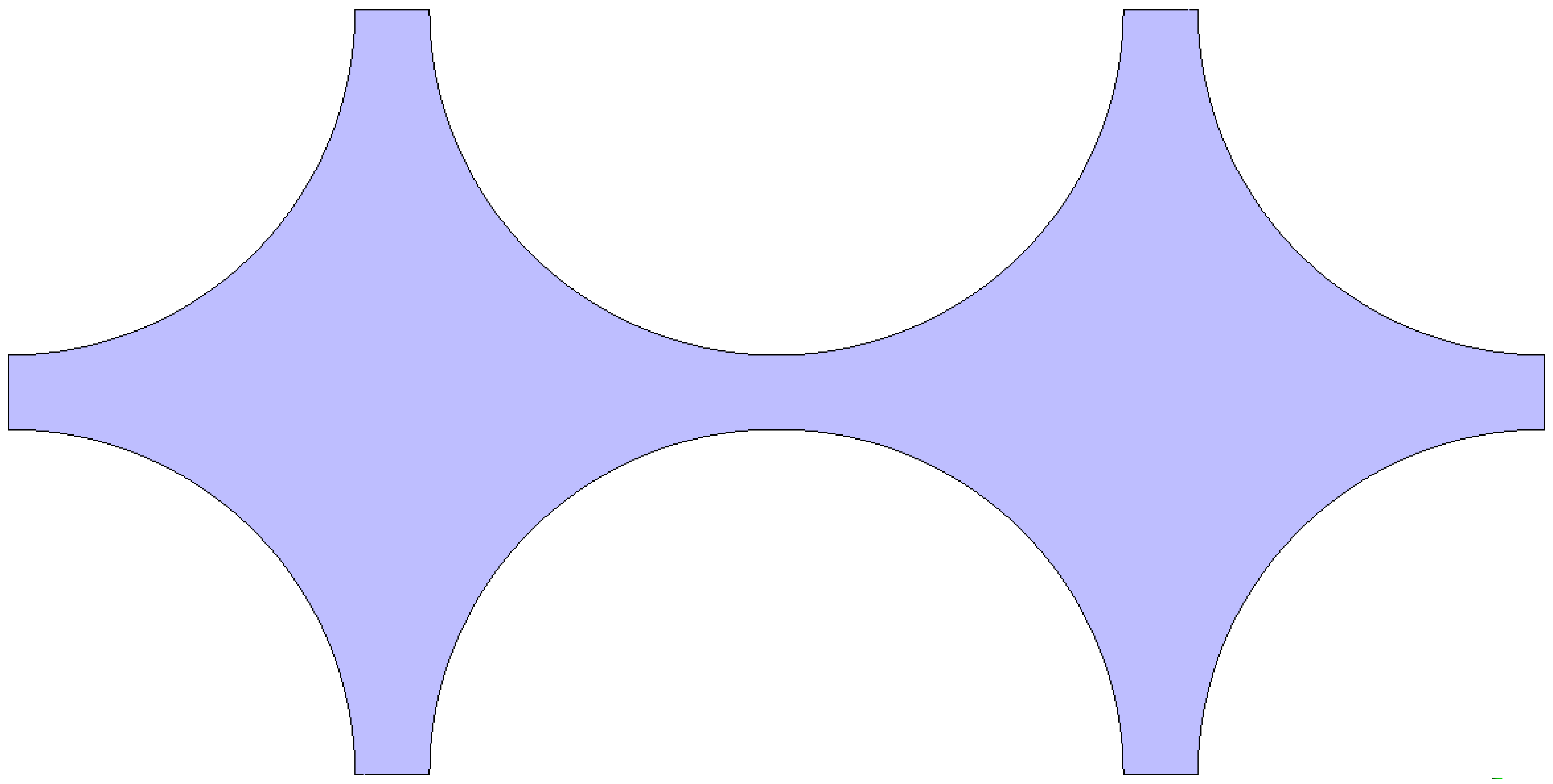
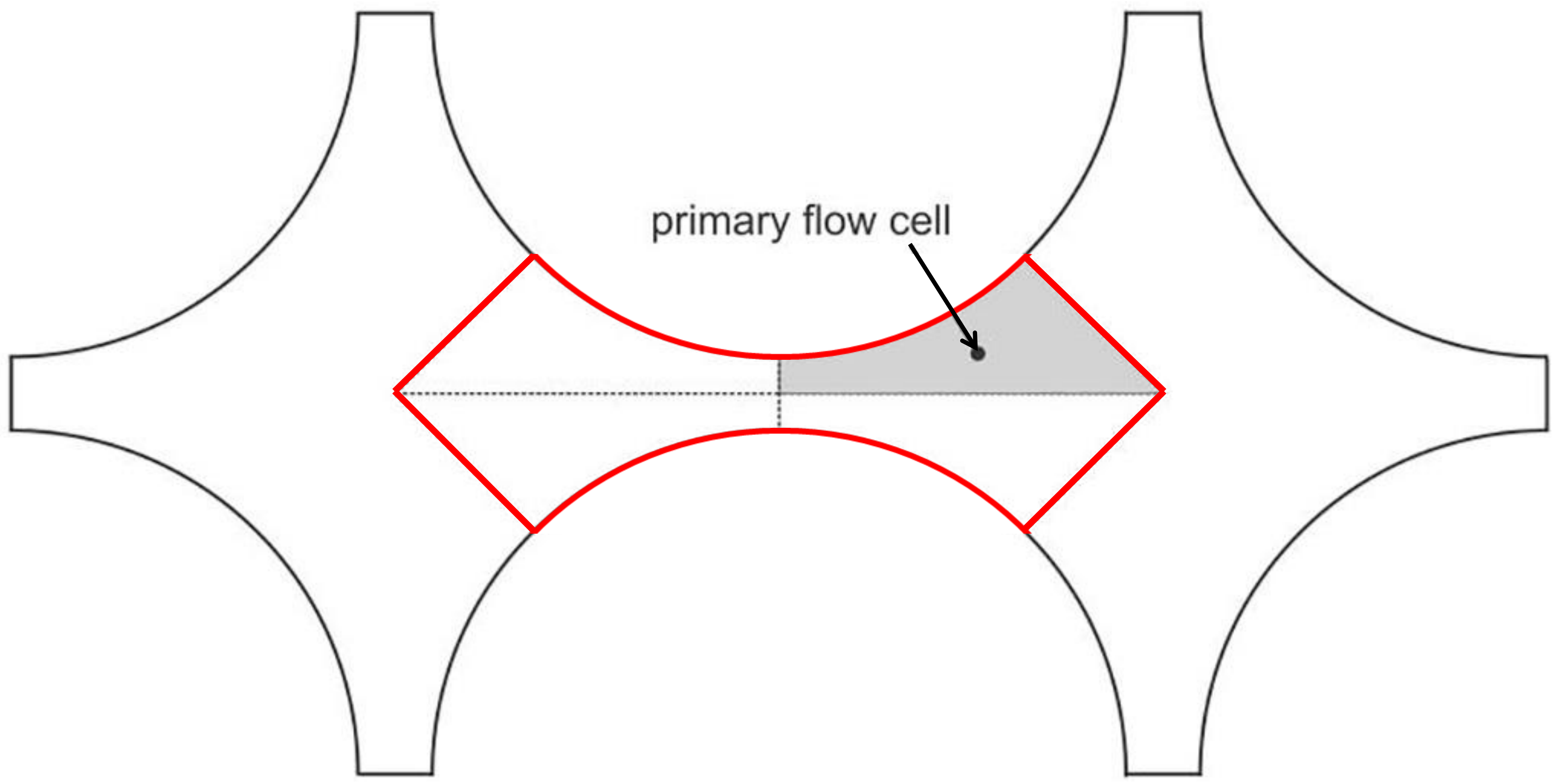


## Cross-sectional domain (CS)



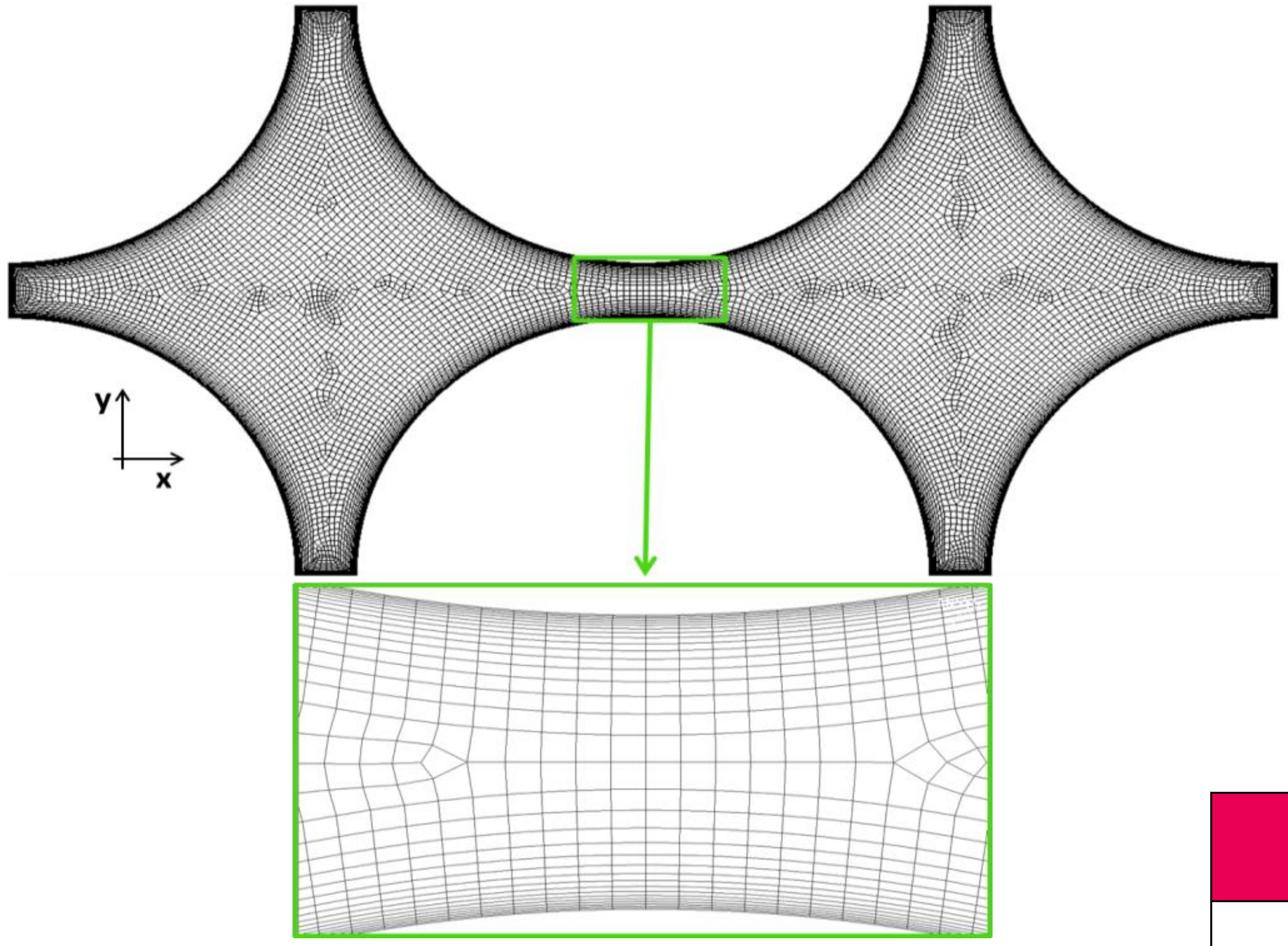

## Length of computational domain

| | Length [m] | Denoted | Re |
|---|---|---|---|
| Based on reference test section | 9.14 | L | 49 000 |
| Based on calibration study* | 2.285 | ¼ L | 9 800 |

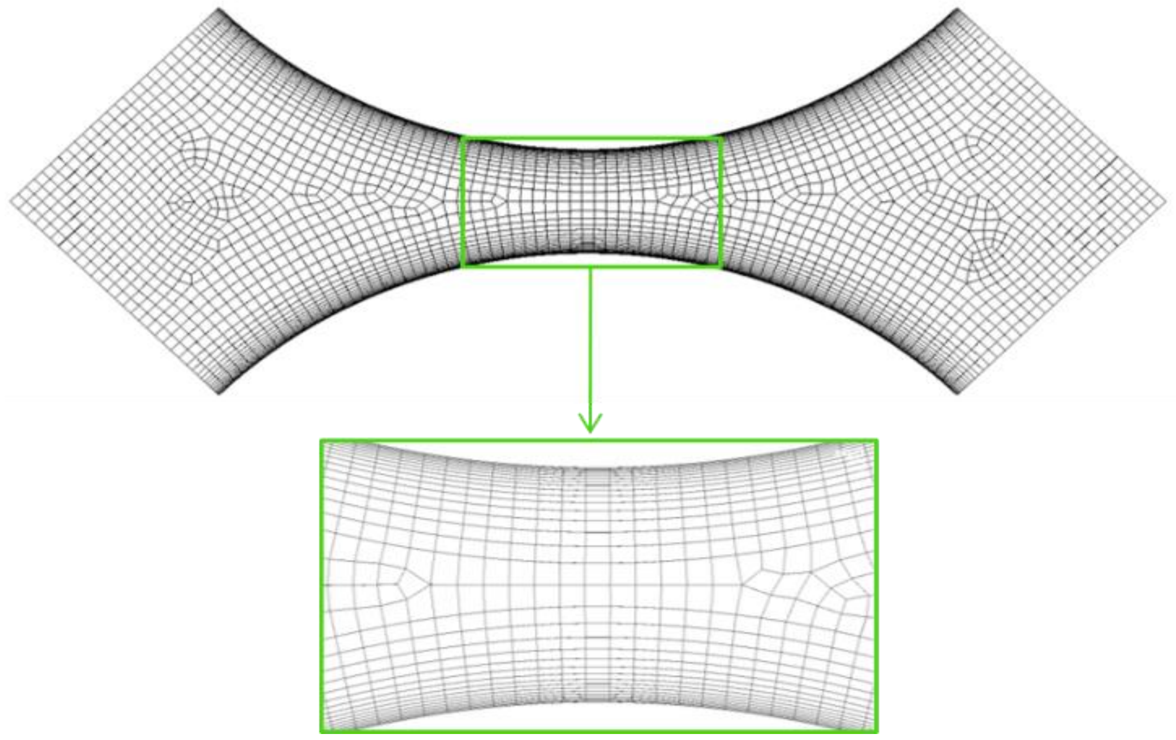
*A. SHAMS and T. KWIATKOWSKI, "**Towards the Direct Numerical Simulation of a closely-spaced bare rod bundle**," Ann. Nucl. Energy 121, 146, Elsevier Ltd (2018); https://doi.org/10.1016/j.anucene.2018.07.022

# Mesh

## Full cross-section domain (F)




## Cross-sectional domain (CS)



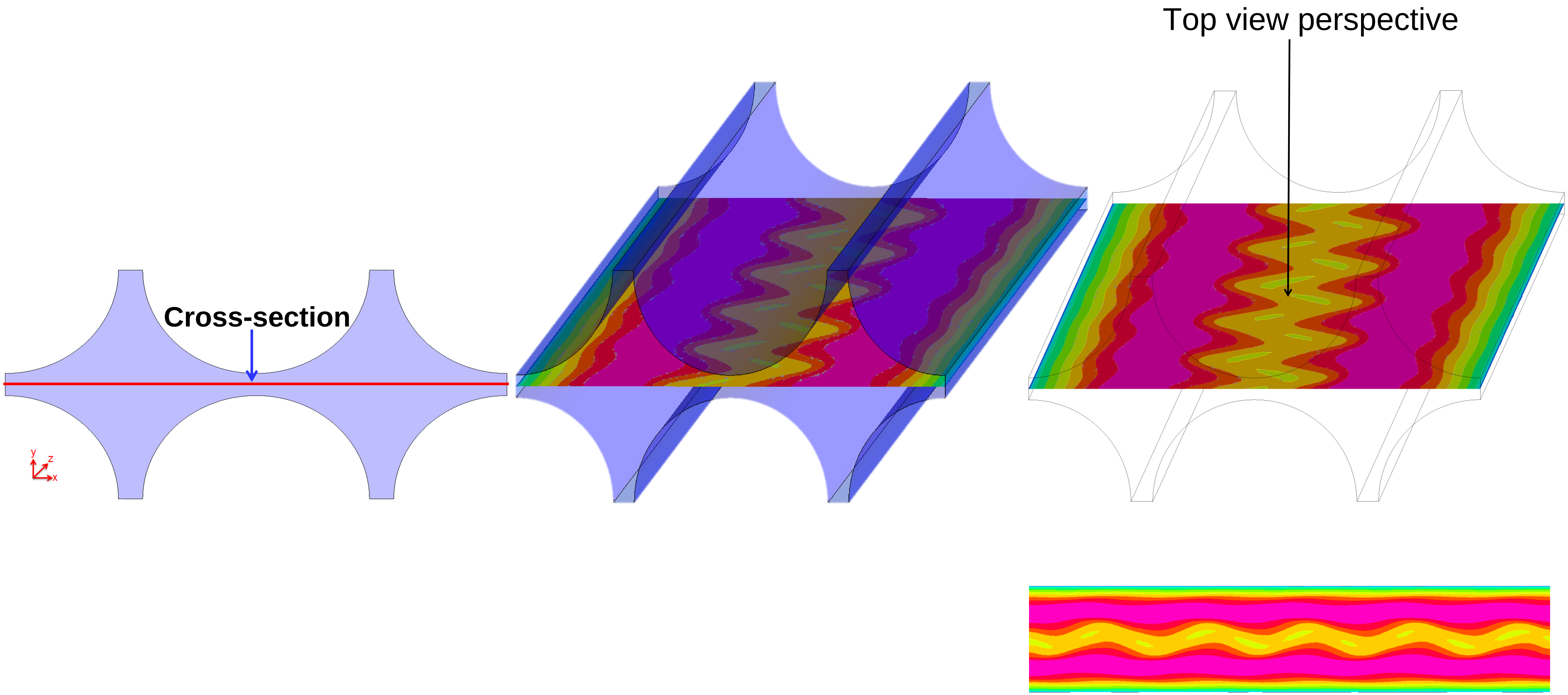
| Domain | Length of domain | No of elements [mln] |
|---|---|---|
| Full cross-section | L | 6.8 |
| | ¼ L | 1.7 |
| Cross sectional | L | 1.6 |
| | ¼ L | 0.4 |

# Hooper case

## Numerical model

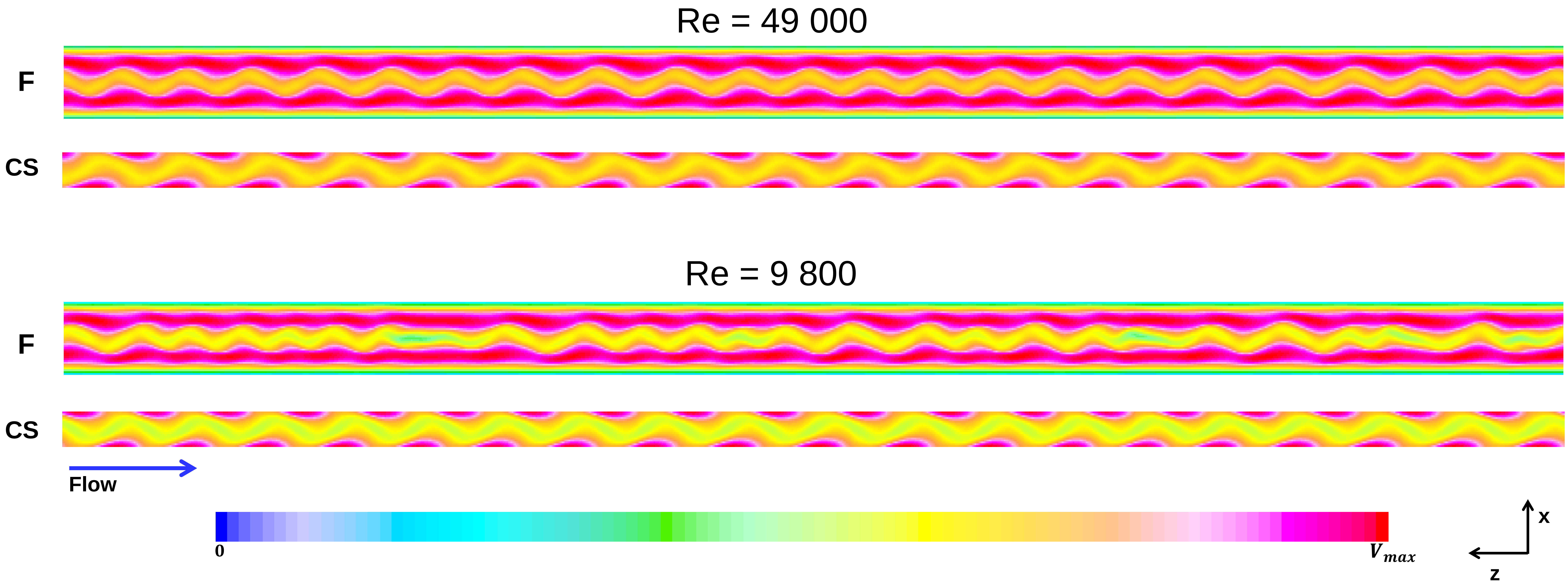
- Main characteristics of the URANS computations
  - ANSYS Fluent v 17.2.0 CFD code
  - URANS: k-ω SST model
  - Second order upwind schemes
  - Mesh (y+ < 1)

# Cross-section for post-processing purposes



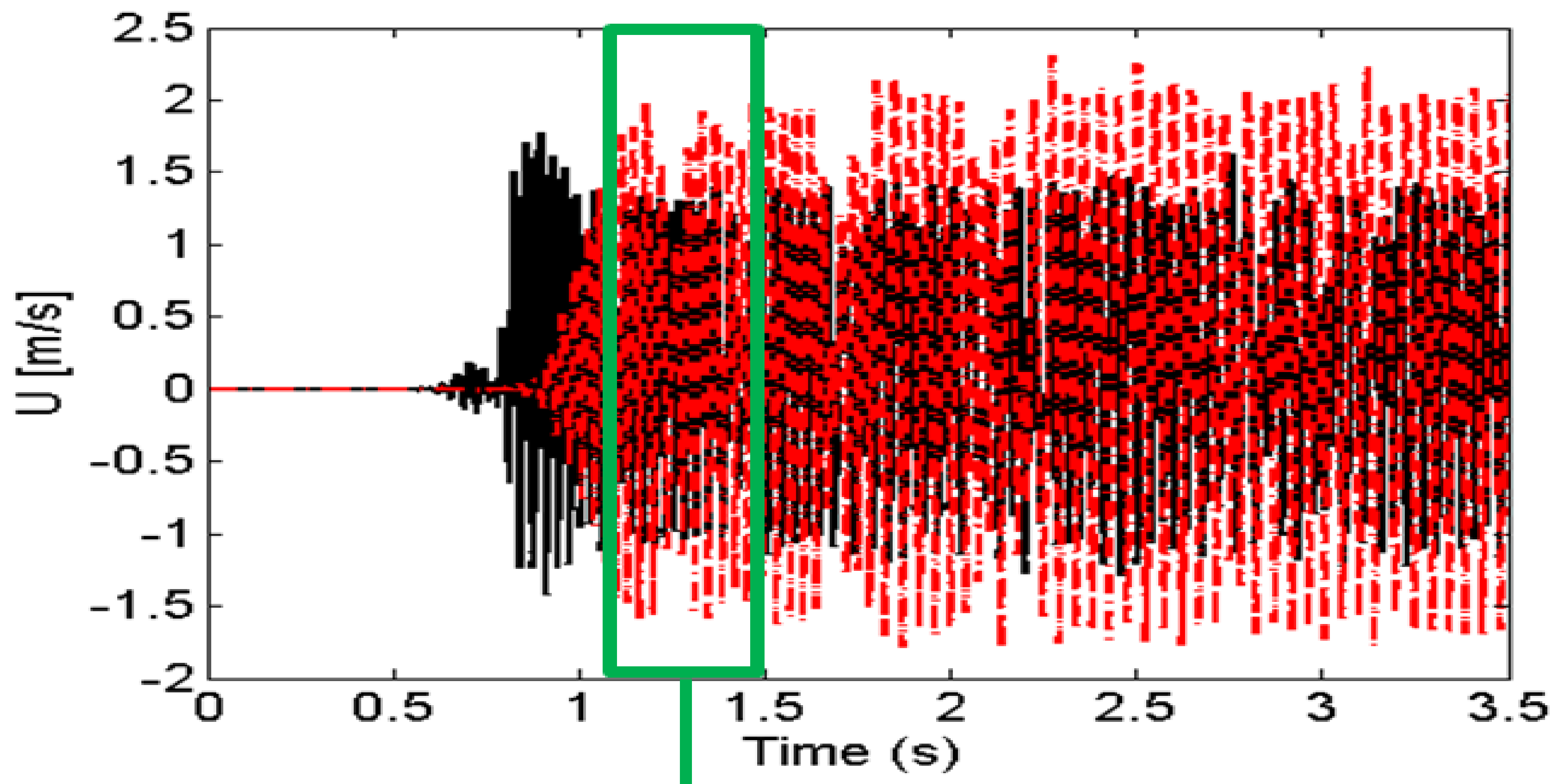
# Gap instability

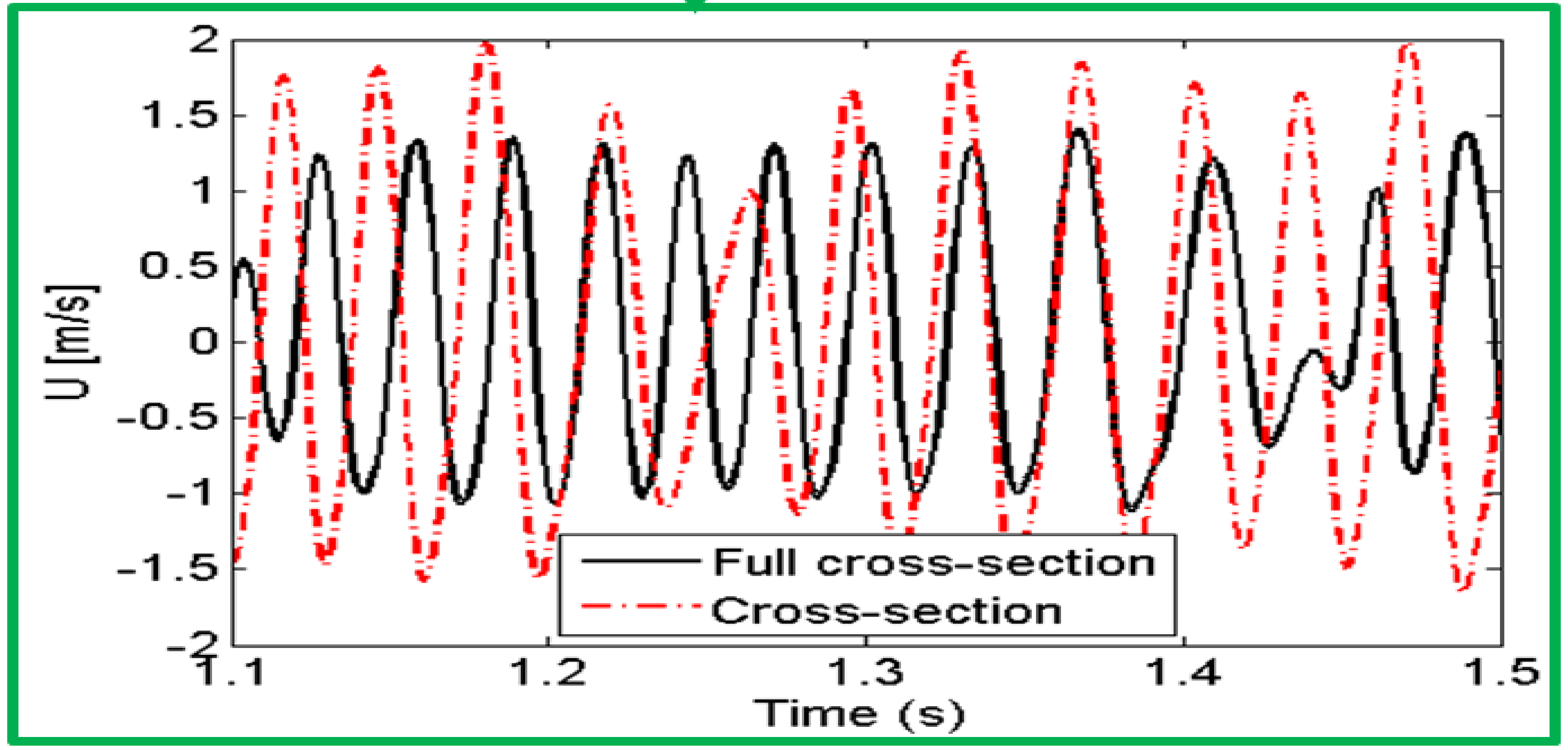
## Velocity field, L = 9.14 m



# Gap instability

## Axial pulsations, Re = 49 000



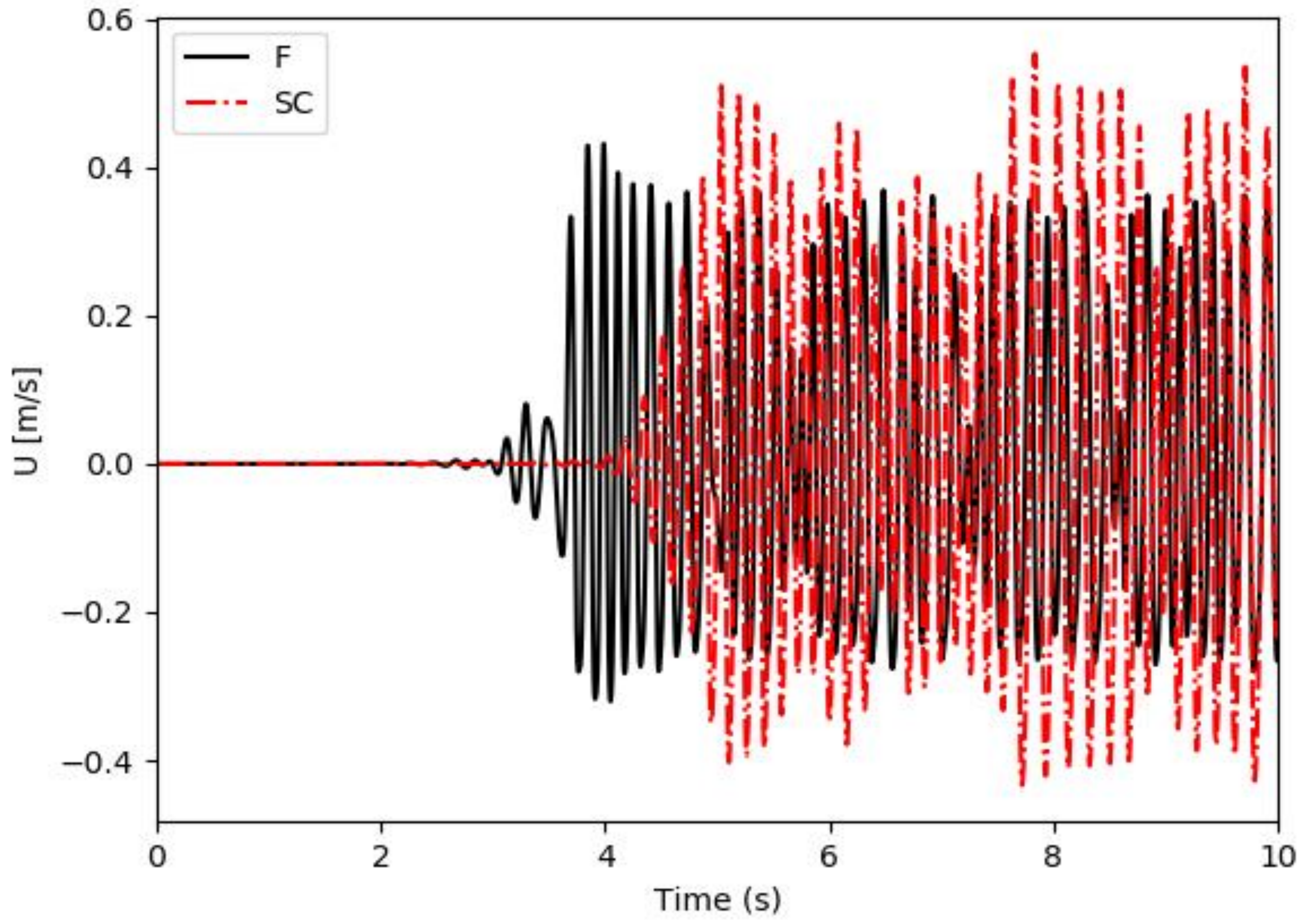

Observations:

- in the cross-sectional domain (red dashed lines) pulsations appeared slightly later
- analyzed axial velocity fluctuations are bigger than ones observed in full cross-section domain (black line). Some of the analyzed values are higher than ± 2m/s.

The measured axial velocity fluctuation in the Hooper experiment varied within ± 1.5 m/s including the experimental error.

# Gap instability

## Axial pulsations, Re = 9 800



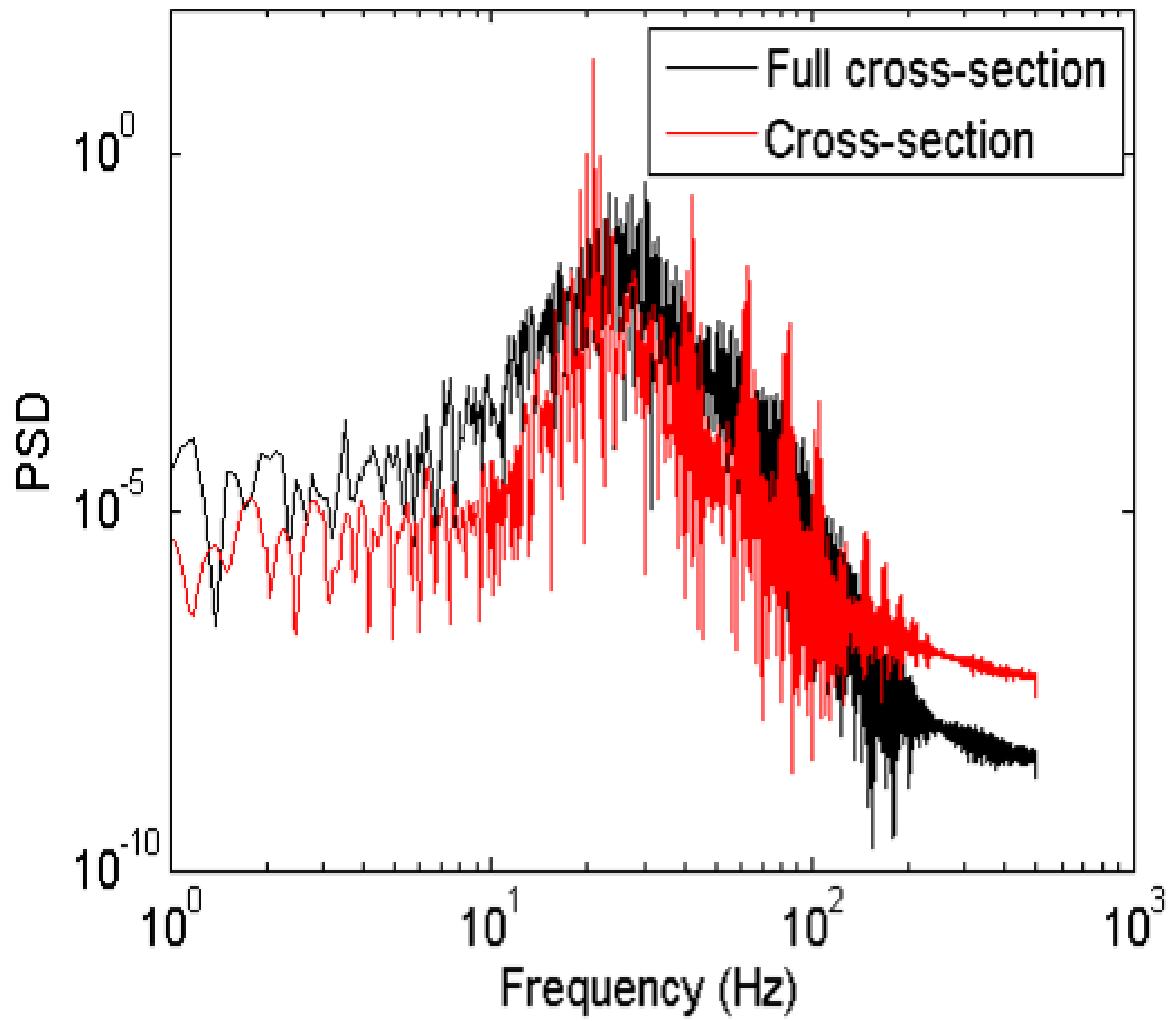

Observations:

- in the cross-sectional domain (red dashed line) pulsations appeared slightly later
- analyzed axial velocity fluctuations are bigger than ones observed in full cross-section domain (black line).

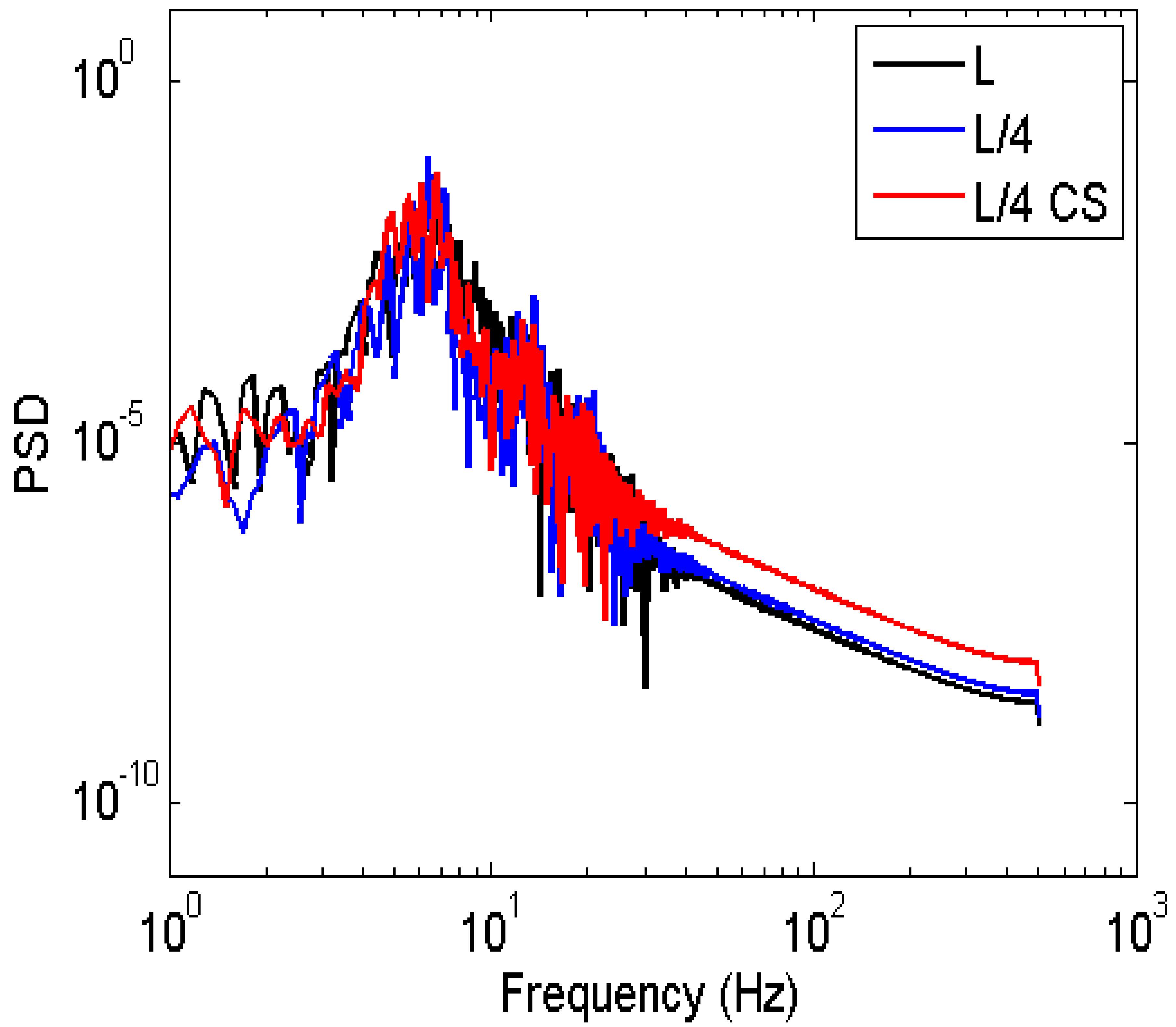
# Gap instability

## Characteristic frequency

**Re = 49 000**

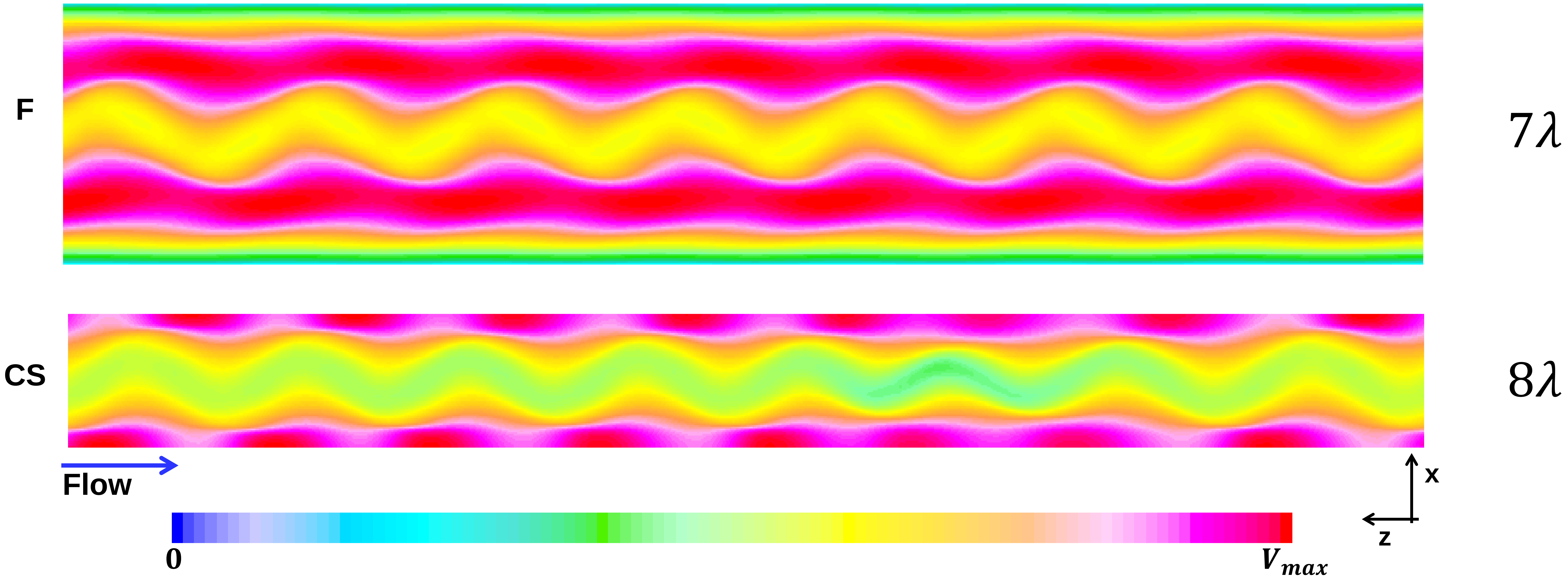



**Re = 9 800**



# Gap instability

**Re = 9800, ¼ L**



# Occurrence of flow pulsation

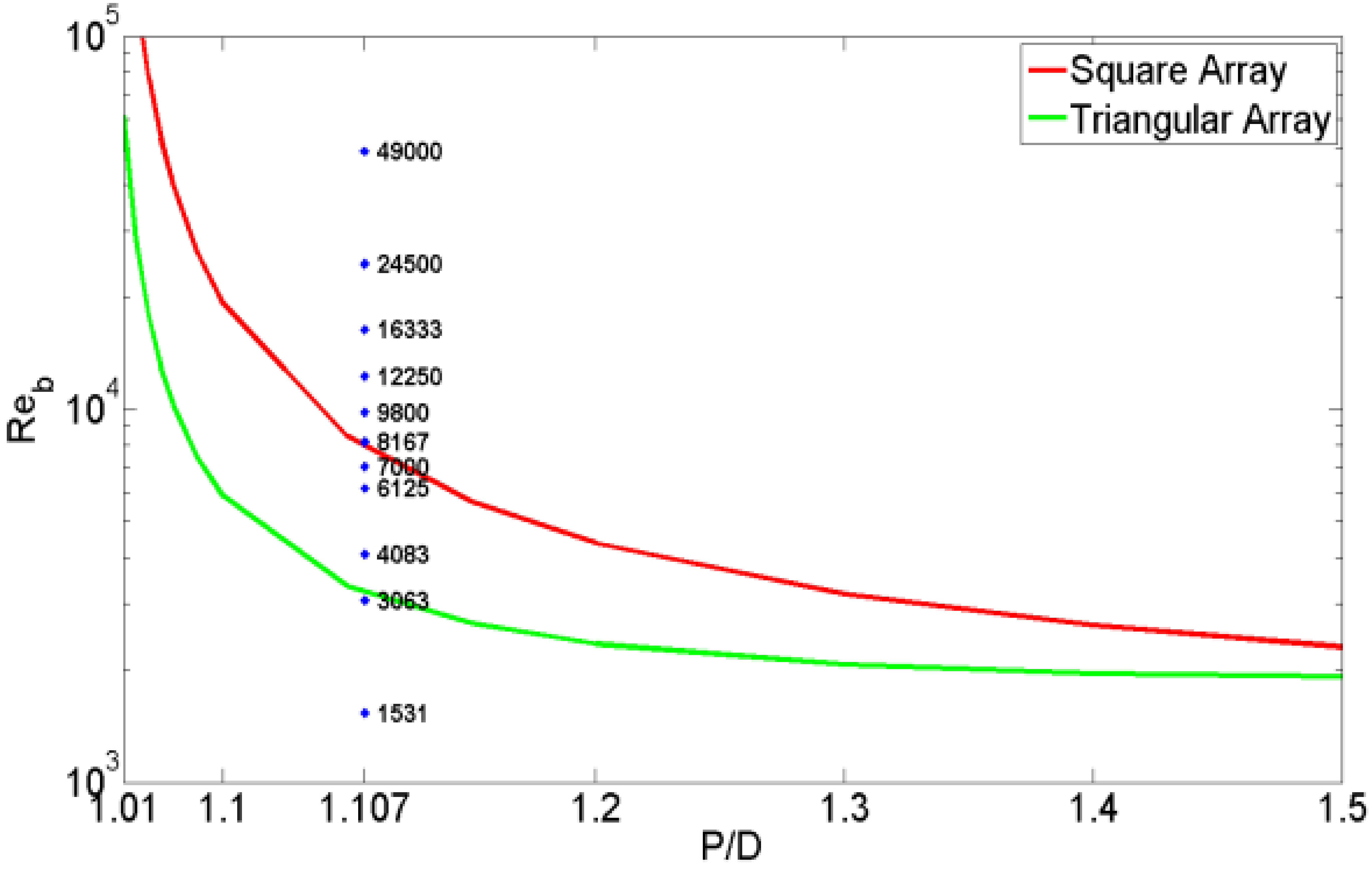
- Influence of the cross-section size domain

- Laminar flow regime

- Influence of the rod gap width

# Gap vortex street

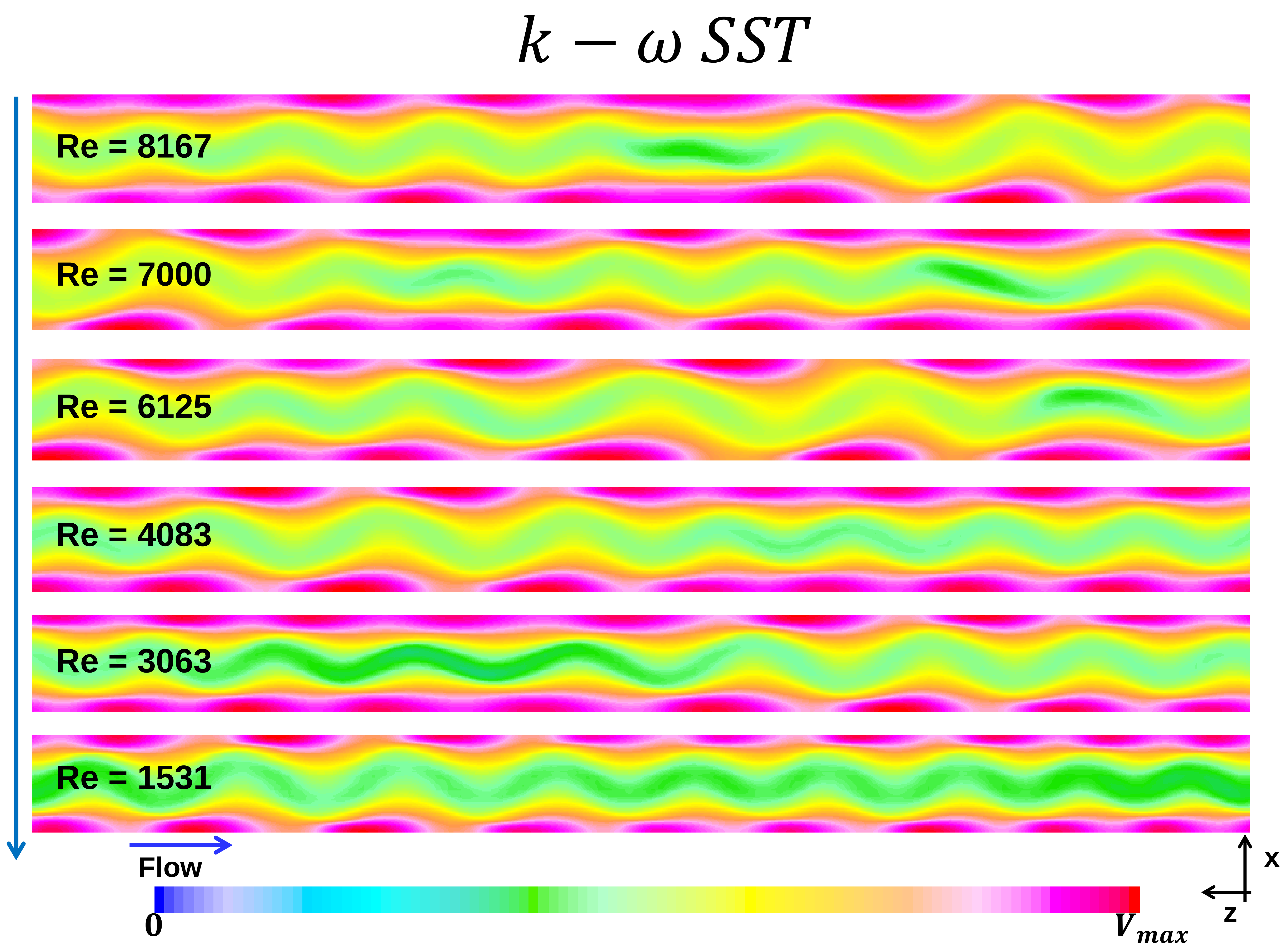
## Laminar flow regime

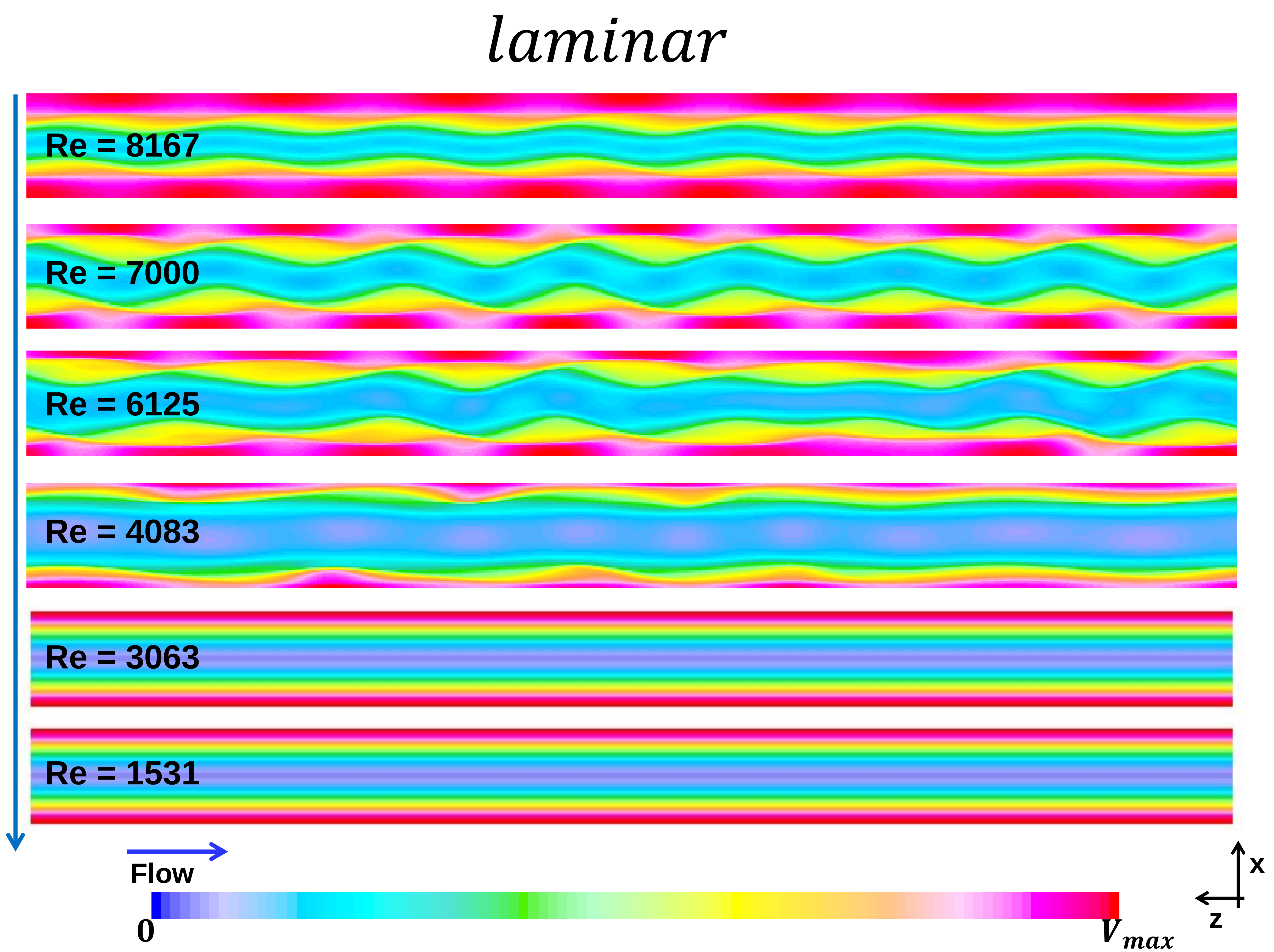



* H. RAMM, K. JOHANNSEN, and N. E. TODREAS, “**Single phase transport within bare rod arrays at laminar, transition and turbulent flow conditions**” Nucl. Eng. Des. **30** 2, 186 (1974); https://doi.org/10.1016/0029-5493(74)90164-2.

# Gap vortex street

## Laminar flow regime



# Occurrence of flow pulsation

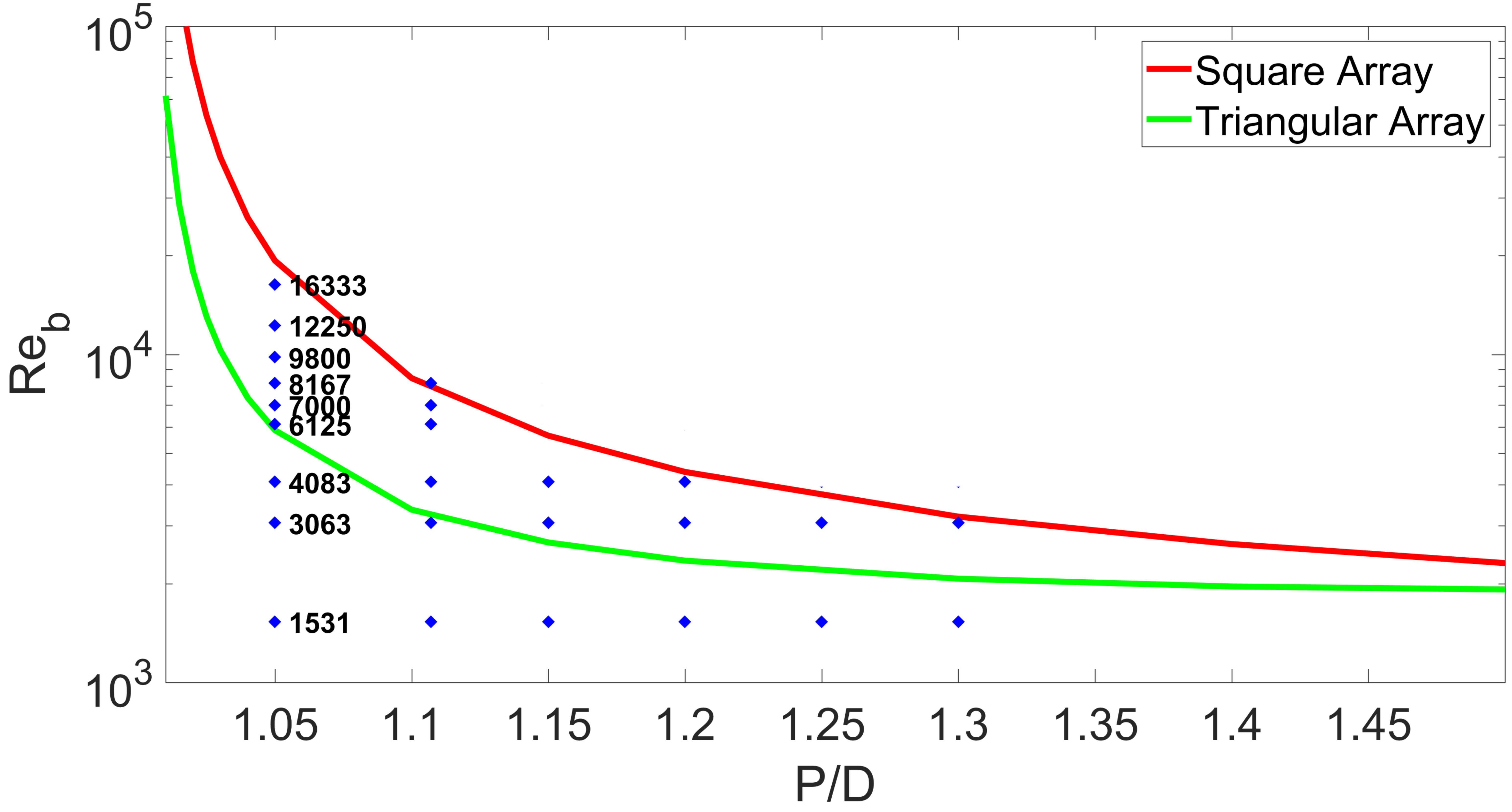
- Influence of the cross-section size domain

- Laminar flow regime

- Influence of the rod gap width

# P/D ratio

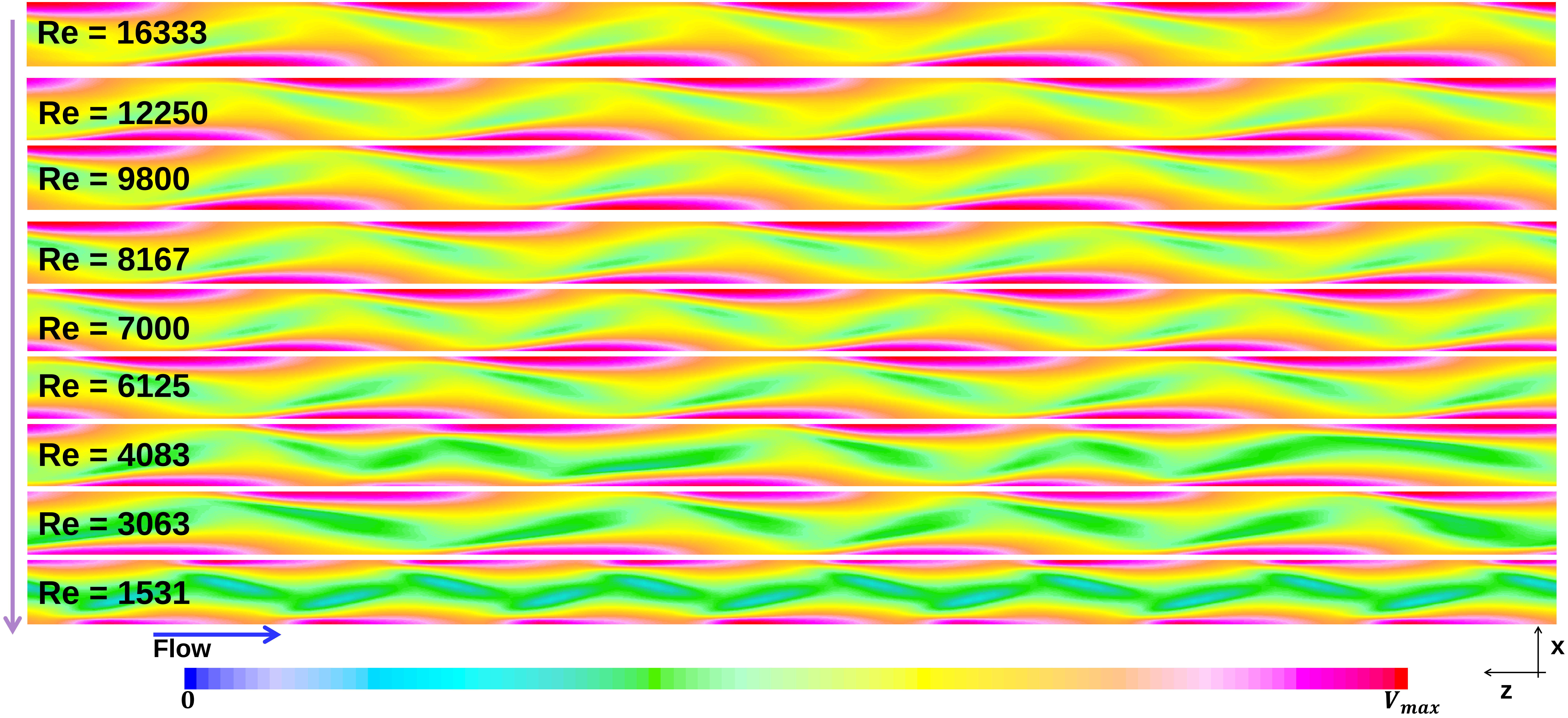
## Investigated cases




| P/D | Re |
|---|---|
| 1.05 | 1531, 3063, 4083, 6125, 7000, 8167, 9800, 12250, 16333 |
| 1.15 | 1531, 3063, 4083, |
| 1.2 | 1531, 3063, 4083, |
| 1.25 | 1531, 3063 |
| 1.3 | 1531, 3063 |

# P/D ratio

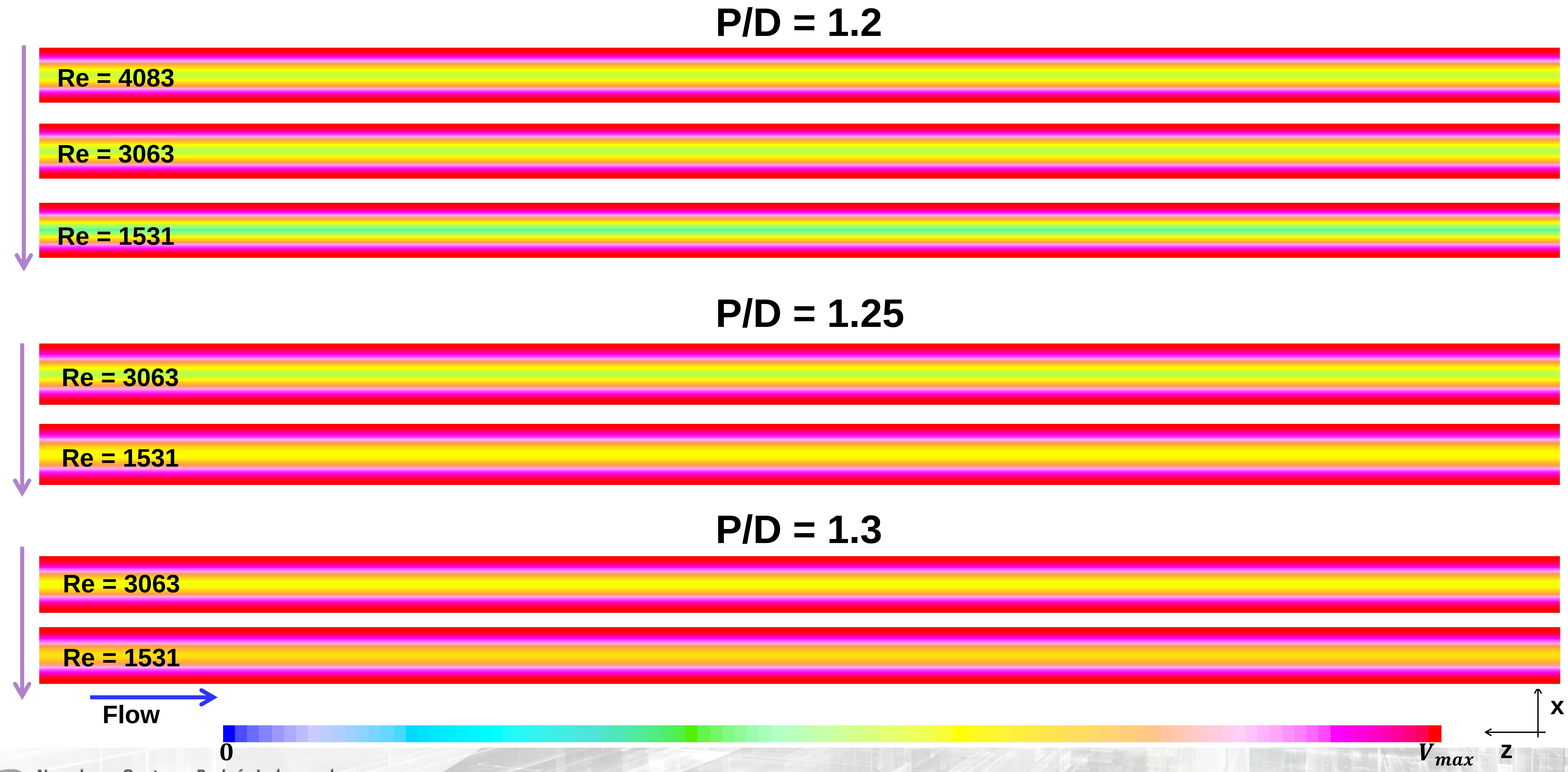
1.05



Re = 16333
Re = 12250
Re = 9800
Re = 8167
Re = 7000
Re = 6125
Re = 4083
Re = 3063
Re = 1531
Flow
0
$V_{max}$
x
z

# P/D ratio
**1.15**

# P/D ratio



P/D = 1.2
Re = 4083
Re = 3063
Re = 1531
P/D = 1.25
Re = 3063
Re = 1531
P/D = 1.3
Re = 3063
Re = 1531
Flow
0
$V_{max}$
x
z

# Summary

- The gap vortex street formation in the rod bundle with square configuration upon certain conditions was investigated.
- The influence of the size of the cross-section domain was assessed. It was shown that the size of the numerical domain influence the characteristics of appearing axial flow pulsations.
- Secondly, a detailed study of flow characteristics in the laminar flow regime concerning the square arranges rod bundle configuration has been assessed. It was found, that there is a critical Reynolds number at which the laminar flow becomes unstable.
- In the last part, the influence of the p/d ratio on the gap vortex street formation has been qualitatively presented. It was not possible to reproduce the flow pulsations for a loosely spaced rod bundle configuration.
- The obtained results have shown the prominent impact on the flow characteristics, such as macroscopic axial flow pulsations, wavelength and the dominant frequency of the pulsation in the investigated cases.

# Acknowledgments


- The simulations presented here were performed on the **Świerk Computing Centre** in the Department of Complex System at the National Centre for Nuclear Research, Poland.
- The work has been carried out within the framework of the **PRELUDIUM-17** project and has received funding from the **National Science Center** (Poland) under grant agreement No **2019/33/N/ST8/00530**.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# Thank you for attention!

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