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GO-VIKING

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ALAIN 5x5 PWR rod bundle experiment and benchmark setup

Authors : Dr. Hidajet HADZIC (Framatome GmbH)

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Project officer: Panagiotis MANOLATOS

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Summary

The GO-VIKING deliverable D2.3 is concerned with providing the experimental data from the flow-induced vibration tests with a reduced 5x5 pressurized water reactor fuel assembly performed by Framatome in the ALAIN test loop in Erlangen. In this context, the document provides a description of the test setup, test fuel assembly, boundary conditions, measuring techniques, test parameters and a compilation of the experimental results aimed to be used in the frame of the GO-VIKING project. The data provided by this deliverable will be used for validation of numerical simulation approaches dedicated to addressing the FIV in fuel assemblies to be developed within the Work Package 2 (WP2) of the GO-VIKING project. The configuration investigated in the experimental studies described in this report form the basis for the Benchmark 2 of the WP2.

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Abbreviations and acronyms

Acronym	description
CCD	Charge-Coupled Device
CFD	Computational Fluid Dynamics
CT	Cladding Tube
DAQ	Data Acquisition
FA	Fuel Assembly
FFT	Fast Fourier Transform
FIV	Flow-Induced Vibration
FR	Fuel Rod
FSI	Fluid Structure Interaction
GO-VIKING	Gathering expertise On Vibration ImpaKt In Nuclear power Generation
GT	Guide Tube
LDA	Laser-Doppler Anemometry
PWR	Pressurized Water Reactor
RMS	Root Mean Square
SG	Spacer Grid
WP	Work Package

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Summary

The GO-VIKING deliverable D2.3 is concerned with providing the experimental data from the flow-induced vibration tests with a reduced 5x5 pressurized water reactor fuel assembly performed by Framatome in the ALAIN test loop in Erlangen. In this context, the document provides a description of the test setup, test fuel assembly, boundary conditions, measuring techniques, test parameters and a compilation of the experimental results aimed to be used in the frame of the GO-VIKING project. The data provided by this deliverable will be used for validation of numerical simulation approaches dedicated to addressing the FIV in fuel assemblies to be developed within the work package 2 of the GO-VIKING project. The configuration investigated in the experimental studies described in this report form the basis for the Benchmark 2 of the work package 2.

Keywords

Flow-Induced Vibration, FIV, Flow Test, LDA, Laser Triangulation

1. Purpose

The GO-VIKING deliverable D2.3 is concerned with providing experimental data from the flow-induced vibration (FIV) tests with a reduced 5x5 pressurized water reactor (PWR) fuel assembly (FA) performed by Framatome in the ALAIN test loop. In this context, the document provides a description of the test setup, test fuel assembly, boundary conditions, measuring techniques, test parameters and a compilation of the experimental results aimed to be used in the frame of the GO-VIKING project.

The data provided by this deliverable will be used for validation of numerical simulation approaches dedicated to addressing the FIV in fuel assemblies to be developed within the work package 2 (WP2) of the GO-VIKING project. The configuration investigated in the experimental studies described in this report form the basis for the Benchmark 2 of the WP2.

The overall objective of GO-VIKING project is the increase the expertise and improvement of the tools and skills of the European nuclear stakeholders in the analysis of complex FIV phenomena, which in turn will maintain and further enhance nuclear plant operation and safety. This will be accomplished by making available existing and new experimental results and improved numerical approaches for the evaluation of FIV in nuclear power plants.

The data provided in this deliverable will support the achievement of the GO-VIKING project objectives through its contribution to development of numerical simulation approaches for analysis of FIV in fuel assemblies. Because of its specific configuration based on use of real components and incorporating all relevant features of a real PWR fuel assembly, this benchmark will also contribute to improvement of the understanding of complex FIV phenomena in fuel assemblies. Furthermore, the numerical simulation methods developed within this benchmark are expected to be applicable to FIV analysis of full-scale fuel assemblies. Although smaller than full scale fuel assemblies, the configuration described in this report is challenging for numerical simulation. Besides complex physical phenomena that require the use of high level multi-physics modelling approach, a big challenge represents also the computational effort required for its simulation. Therefore, the implementation of efficient solutions for coupled FSI simulations, which is one of the main objectives of WP2, will be an essential part of the benchmark.

2. Introduction

Understanding the complex behaviour of fuel assemblies in PWR requires experimental investigations of system vibrational characteristics (both natural and induced by fluid flow) as well as the investigation of flow behaviour of the cooling medium within fuel assembly. For this purpose, experimental investigations to study the vibration behaviour on reduced-scale 5x5 fuel assemblies were organized by Framatome. The main objectives of the experimental research were:

- Quantitative evaluation of natural and flow-induced vibrations of reduced-scale fuel assemblies equipped with a specific spacer grid (SG) design,

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- Determination of the fluid flow behaviour within the fuel assembly in presence of the vibrating solid structures.

For investigations of the vibrational behaviour of the reduced FA, laser triangulation systems were applied. Flow measurements were carried out by means of the one-dimensional laser Doppler anemometer (LDA). Experiments were carried out in the research centre of Framatome GmbH in the mini test loop "ALAIN" with a test channel designed to accommodate a 5x5 rod bundle configuration.

The present document contains the description of the test loop, test fuel assembly, measuring systems, the listing of the measurement process parameters and the test results that will be made available for GO-VIKING project.

3. Materials and methods

3.1 Test loop

The experiments were carried out in the "ALAIN" test loop that was operated by the technical centre of Framatome in Erlangen. The principal sketch of the test loop is given in Figure 1. The experimental bench consists of a Plexiglas channel (1) with a 2.3 m long test fuel assembly (2) placed inside the test channel. The test channel has a square cross-section with inner dimensions 69x69 mm, and length of 2.7 m. Usage of the Plexiglas walls has allowed the optical access to the test bundle and application of non-invasive and non-disturbing optical measurements methods. The flow of the operating medium (water) in the loop is forced by the pump (3). Volume flow is controlled by means of the two throttling valves placed upstream (4) and downstream (5) of the test section. In addition, the by-pass section (6) can also be employed for the flow control. In practice, the control and adjustment of the flow is realized only by the valve placed upstream of the test section (4). The volume flow rate of the operating medium in the loop is measured by means of the magneto-inductive flow meter (7).

To prevent transmission of mechanical vibrations generated through the pump to the test section, the rubber absorbers are implemented at inlet (8) and outlet (9) of the test section. To achieve a smooth flow distribution, a flow straightener (10) is implemented at the entrance in the tests section. The temperature of the operating fluid in the test loop is adjusted by means of the heater (11) and/or cooler (12) placed in the storage tank (13). The throttling valve (14) is responsible for control of the cooling capacity. Process medium is filtered by means of the filter (15). The manual deaerator (16) is placed at the top of the test loop.

The test bundle for the "ALAIN" loop is arranged in a 5x5 square matrix built of 23 fuel rods (FR) and 2 guide tubes (GT) (Figure 2). Fuel rods have outer diameter d_{FR} of 9.5 mm and the pitch between rods p is 12.32 mm. The 5x5 spacer grid sections have a width of 66 mm resulting in a nominal side gap between bundle and test channel of 1.5 mm.

Figure 3 shows the test section of the ALAIN loop with systems for measurements of vibration and flow field during tests.

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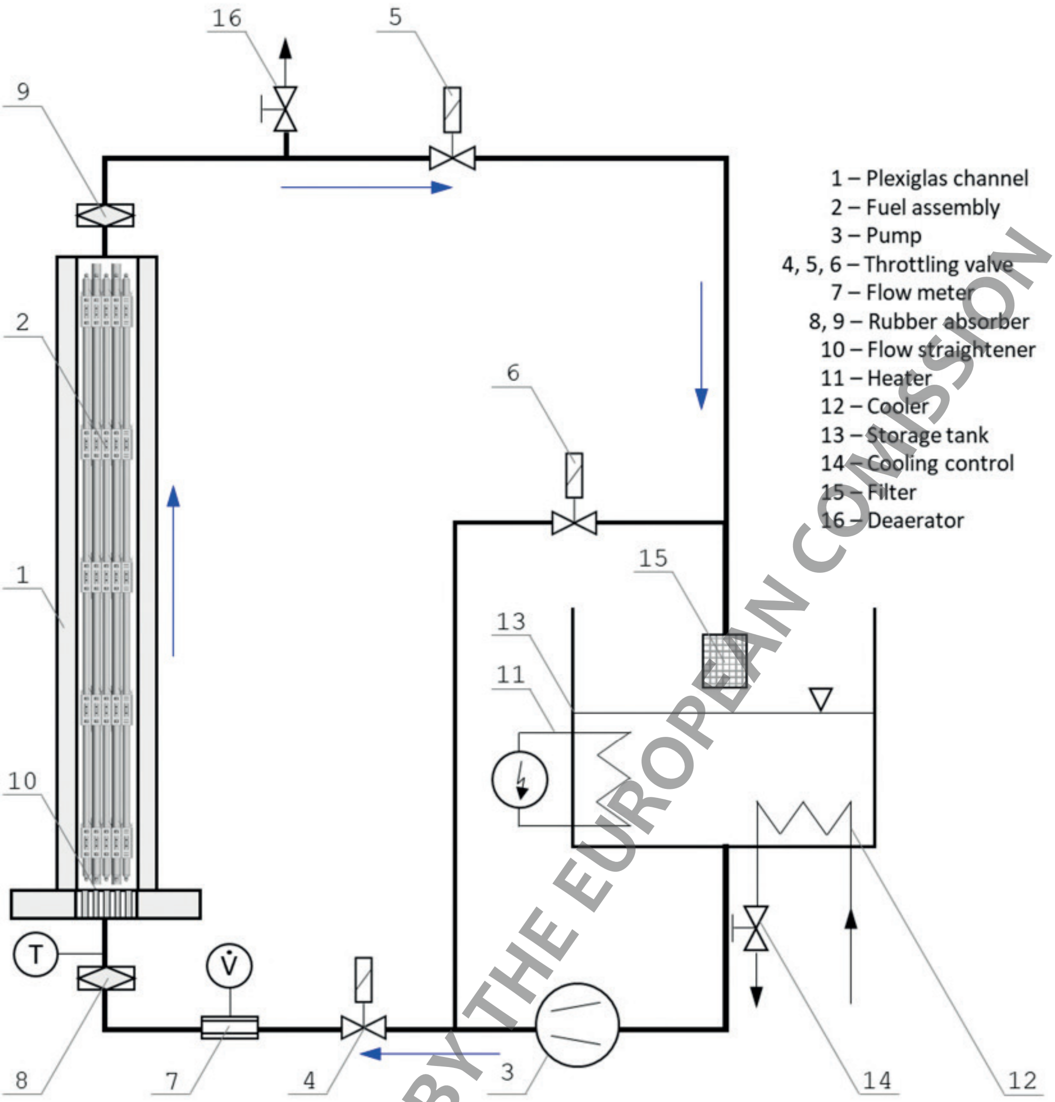

Figure 1: Principal sketch of the "ALAIN" test loop

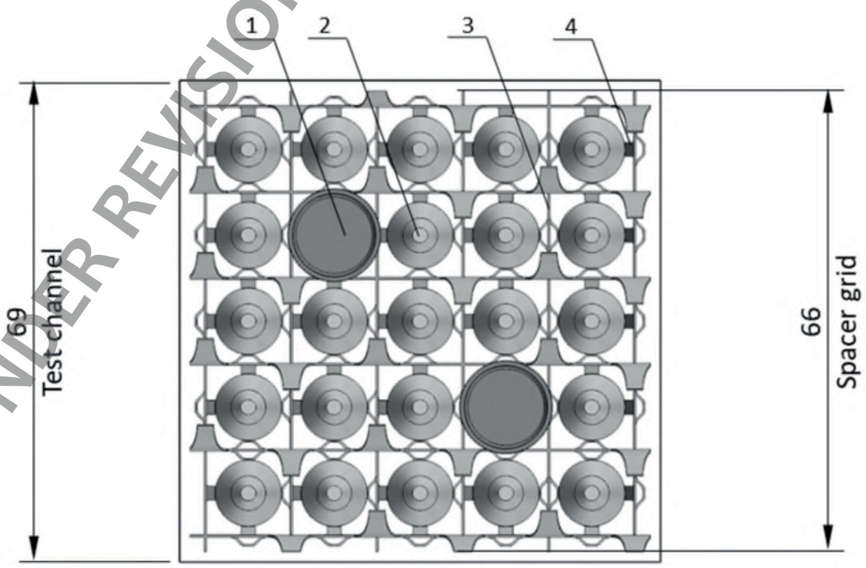

Figure 2: Test bundle and test channel cross-section

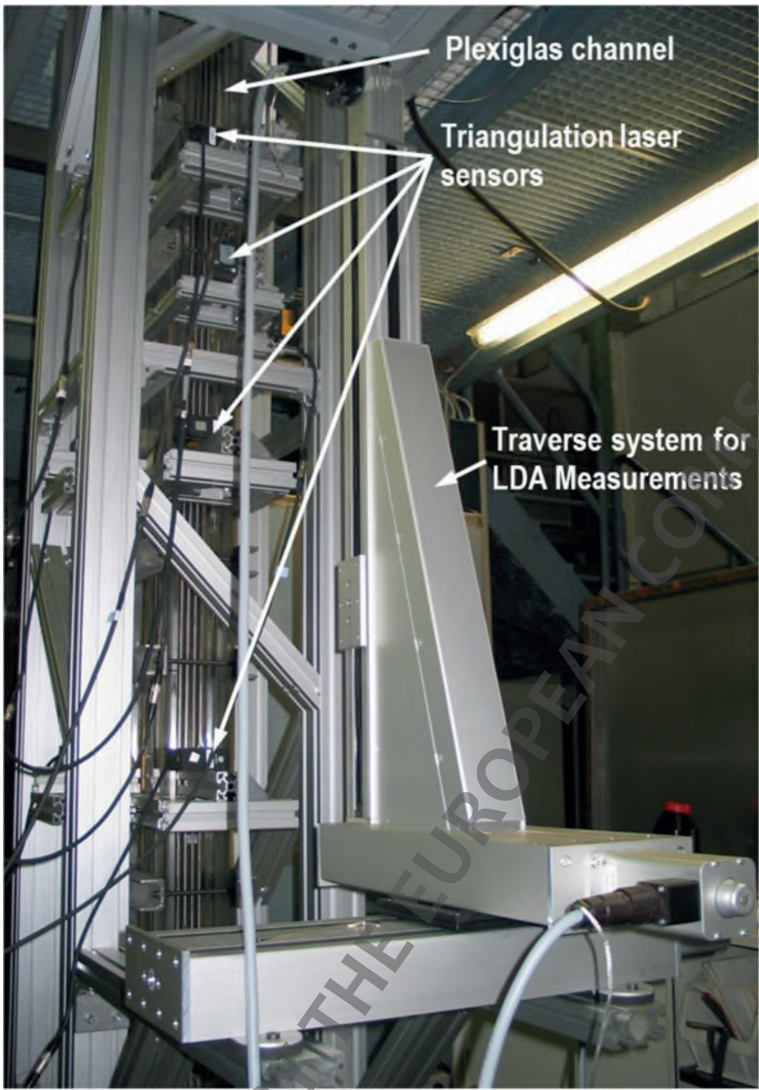

Figure 3: Test section of the "ALAIN" test loop with measurement systems

3.2 Test fuel assembly

An overview of the test fuel assembly is given in Figure 4a. It consists of a 5x5 square rod bundle. Two rod positions are replaced by guide tubes which together with five spacer grids, a top and a bottom plate form the skeleton of the bundle. The 5x5 spacer grid sections are obtained by cutting out from the original 16x16 spacer grids. Spacer grids are connected rigidly to the guide tubes and distributed equidistantly along the bundle providing a span length of 545 mm. The bottom plate, which is cut out from original bottom nozzle filter is fixed to the base plate of the test loop. At the top side an upper plate is implemented with a hold down system to fix the bundle in axial position inside the test channel. The total length of the reduced-scale test fuel assembly corresponding to the distance between lower and upper tie plate is 2305 mm.

The test bundle is equipped with test rods of the length of 2275 mm. An overview of the test rod is provided in Figure 4b. The test rod consists of a cladding tube (CT) with the outer diameter of $d_{\mathrm{CT,out}}$=9.5 mm and the inner diameter of $d_{\mathrm{CT,in}}$=8.22 mm made of Zircaloy. The test rods are filled with Molybdenum pellets to simulate the mass of Uranium oxide pellets in real fuel assemblies. At the bottom side there is a supporting tube and at the top side is a plenum spring which keeps the Molybdenum pellets in position. The rods are clamped in the spacer grid cells in accordance with BOL rod support conditions corresponding to a nominal clamping spring force of 20 N. Main parameters of the test bundle and material properties relevant for the mechanical modelling are summarized in Tables 1, 2 and 3 below.

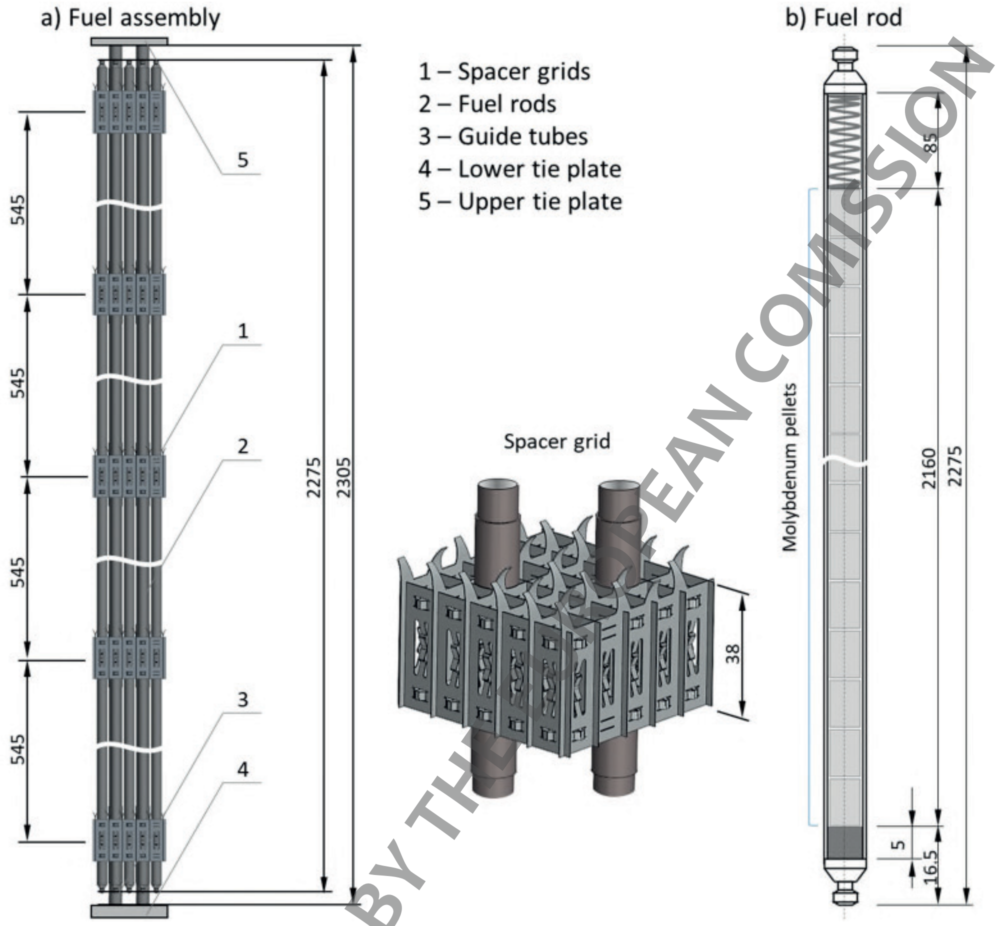

Figure 4: Overview of 5x5 test bundle

Rod arrangement	5x5
Number of fuel rods	23
Number of guide tubes	2
Bundle length	2305 mm
Rod length	2275 mm
Cladding tube outer diameter	9.5 mm
Cladding tube inner diameter	8.22 mm
Guide tube outer diameter	11.96 mm
Guide tube inner diameter	11.05 mm
Rod filling – Mo pellets column	8.05 x 2160 mm
Spacer grid	66 x 38 mm

Table 1: Test bundle main data

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Material	Density [g/cm³]	E-modulus [GPa]		Parts
		20°C	40°C	
Zircaloy	6.6	98.1	96.79	CT, GT
Alloy 718	8.2			SG
Molybdenum	10.2			pellets

Table 2: Material properties

	Mass (single part) [kg]	Mass (total) [kg]
Fuel rod	1.4011	32.224
Guide tube	0.3366	0.673
Spacer grid	9.183E-02	0.4592

Table 3: Structural mass of single FA parts relevant for mechanical modelling

3.3 Laser triangulation system

Laser triangulation systems are used for vibration measurements. Such systems are widely used highly precise measurement tools for vibration analysis. One of the main advantages of the triangulation system is its compact and simple design that allows the application of the systems under industrial conditions. The scheme of the laser triangulation system applied during the tests is given in Figure 5a. The principle of the operation can be explained as follows: a laser beam generated in the optical head is focused on the surface of the measured object and partially reflected towards the CCD (charge-coupled device) sensor. The motion of the measured object evokes the laser beam displacement on the CCD sensor. The beam displacement is proportional to the voltage generated by the sensor. The voltage signal is amplified and registered by means of the data acquisition system (DAQ).

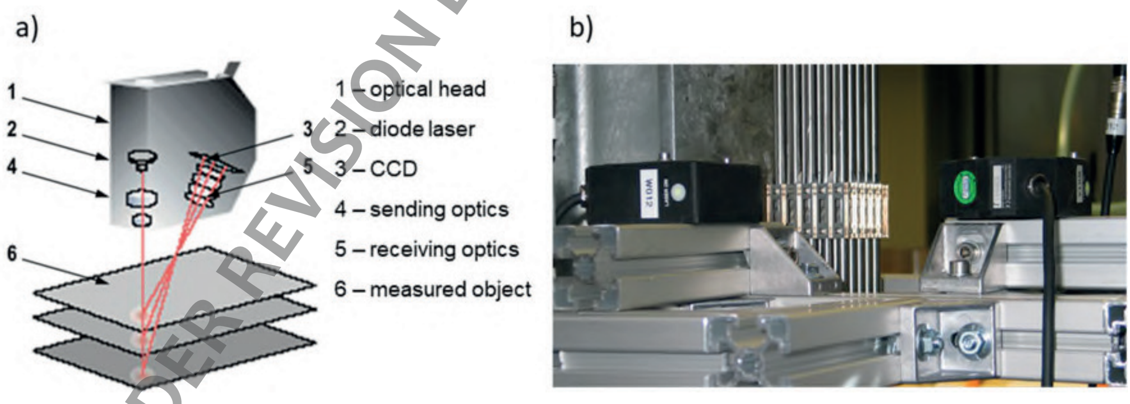

Figure 5: Keyence triangulation system for vibration analysis: a) operation principal, b) application to measurement of fuel assembly displacement

For measurement of the fuel assembly vibration six triangulation sensors (optical head: Keyence LK-081, amplifier: LK-2101) were used (see Figure 5b). Two additional sensors (optical head: Keyence LK-G152, amplifier Keyence LK-G3001) were applied for measurements of the fuel rod vibration. The specification of the sensors is given in Table 4. The data acquisition system contained 36 channels DAQ card (National Instruments) and Lab View program.

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Before starting the measurements all the sensors were calibrated in the system with Plexiglas-water interface. Based on the calibration results the correction factor was established and applied in the Lab View software.

Manufacturer		Keyence	Keyence
Model	Sensor head	LK-081	LK-G 152
	Controller	LK-2101	LK-G 3001
Light source	Type	Visible red semiconductor laser	
	Wavelength	670 nm	
Reference distance		80 mm	150 mm
Measuring range		± 15 mm	± 40 mm
Minimum spot diameter (at reference distance)		Approx. 70 µm	Approx. 120 µm
Resolution		3 µm	0.5 µm
Sampling frequency		1024 µs	20, 50, 100, 200, 500, 1000 µs
Power supply		24 VDC±10%	
Current consumption		400 mA max.	
Materials		Sensor head: Aluminium die-cast, Controller: Polycarbonate	

Table 4: Specification of the triangulation systems for vibration measurements

3.4 Laser-Doppler anemometry

Laser-Doppler anemometry is a non-invasive, optical, indirect measurement method that serves for flow investigations in point. Basic LDA system contains laser source, beam separator and/or brag cell, sending and receiving optics, signal detector with amplifier and signal analyser (Figure 6 a). Laser beams are intersected in one point by means of the sending optics. Due to the nature of the laser light in the intersection point, the interference pattern (fringe pattern) of high and low intensity is generated (Figure 6 b).

Its dimensions (δ_x, δ_z, δ_z, δ_f, see Figure 6 b) depend only on the optic parameters (focal length F, diameter of the beam on the front lens D_L, angle between beams θ) and length of the light wave λ and they are calculated as:

$$\delta_x = 4F\lambda/\left(\pi D_L \cos(\theta/2)\right) \quad (1)$$

$$\delta_y = 4F\lambda/(\pi D_L) \quad (2)$$

$$\delta_z = 4F\lambda/\left(\pi D_L \sin(\theta/2)\right) \quad (3)$$

$$\delta_f = \lambda/\left(2 \cdot \sin(\theta/2)\right) \quad (4)$$

If there is a particle in the flow passing through the control volume it scatters the light with fluctuating intensity. The frequency of the fluctuation f_D is proportional to the velocity of the particle. By measuring the frequency of the scattered light fluctuation f_D and knowing the distance between fringes δ_f, the velocity of the particle (following the flow) u_i can be derived:

$$u_i = \delta_f \cdot f_D = \lambda f_D / \left(2 \cdot \sin(\theta/2)\right) \quad (5)$$

Further details on laser Doppler anemometry can be found in Durst *et* al. (1976) and Albrecht *et* al. (2003).

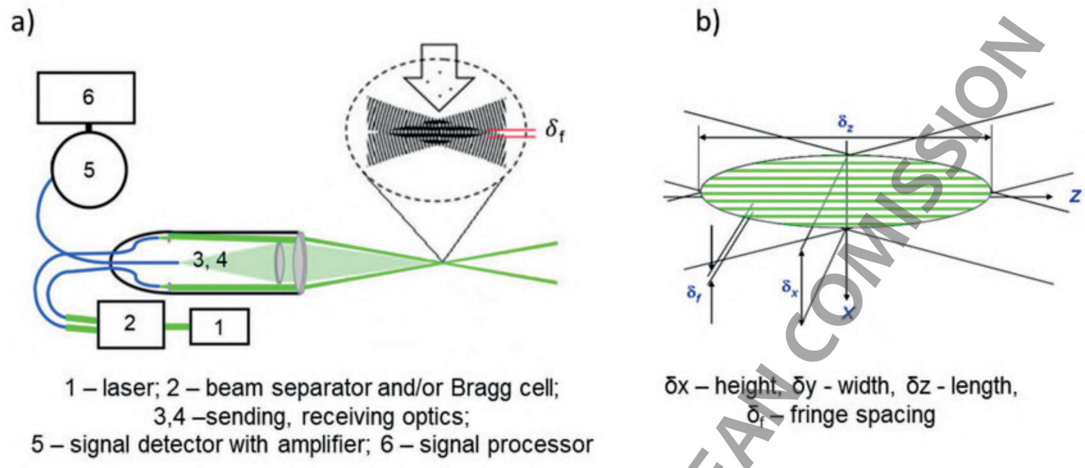

Figure 6: LDA system (a) and measurement volume of laser-Doppler anemometer (b)

During the flow measurements a one-component LDA system (Dantec Dynamics) operating in backscatter mode was used. The system is based on the 100 mW (nominal optical power) Ar-Ion laser (Ion Laser Technology). Measured optical power at the output of the sending probe was about 5 mW. Measurements were carried out utilizing the green light with the wave length λ=514.5 nm. Since the standard optical head did not provide sufficient spatial resolution of the measurement, the beam expander with expansion ratio *E*=1.98 had to be applied to the system. The geometrical specification of the LDA system is given in Table 5.

Hollow glass spheres with mean diameter of 10 µm and density of 1100 kg/m3 were used as tracers during velocity measurements. The positioning of the measurement volume was done by means of a computer-aided traverse system presented in Figure 3.

Optical system	Without beam expander	With beam expander
Beam diameter D_L	1.35 mm	2.673 mm
Beams span *D*	38 mm	75.24 mm
Focal length *F*	400 mm	310 mm
Beams half-angle $\theta/2$	2.72 °	6.919 °
Height of the meas. volume δ_x	~0.26 mm	~0.1 mm
Width of the meas. volume δ_y	~0.26 mm	~0.1 mm
Length of the meas. volume δ_z	~5.4 mm	~0.84 mm
Fringe spacing δ_f	~7.2 µm	~2.84 µm
Number of fringes N_f	35	35
Optical system	Without beam expander	With beam expander

Table 5: Geometrical specification of the LDA system

3.5 Test conditions and parameters

3.5.1 Impact tests

The impact tests were used to determine natural frequencies of the investigated fuel assembly. The tests were carried out in air under ambient conditions. Assembled bundle as well as the skeleton made of guide tubes and spacer grids were investigated. Impact positions and directions are presented in Figure 7.

Natural frequencies of the system are determined based on the measurement of the lateral displacement of spacer grids with laser triangulation systems and further processing of the measurement data with fast Fourier transform (FFT). Measurement time during impact tests was 600 s. During each test impact at corresponding spacer grid position was repeated every 60 s in case of the skeleton measurements and every 30 s in case of the complete bundle examination. Sampling frequency in both cases was 500 Hz.

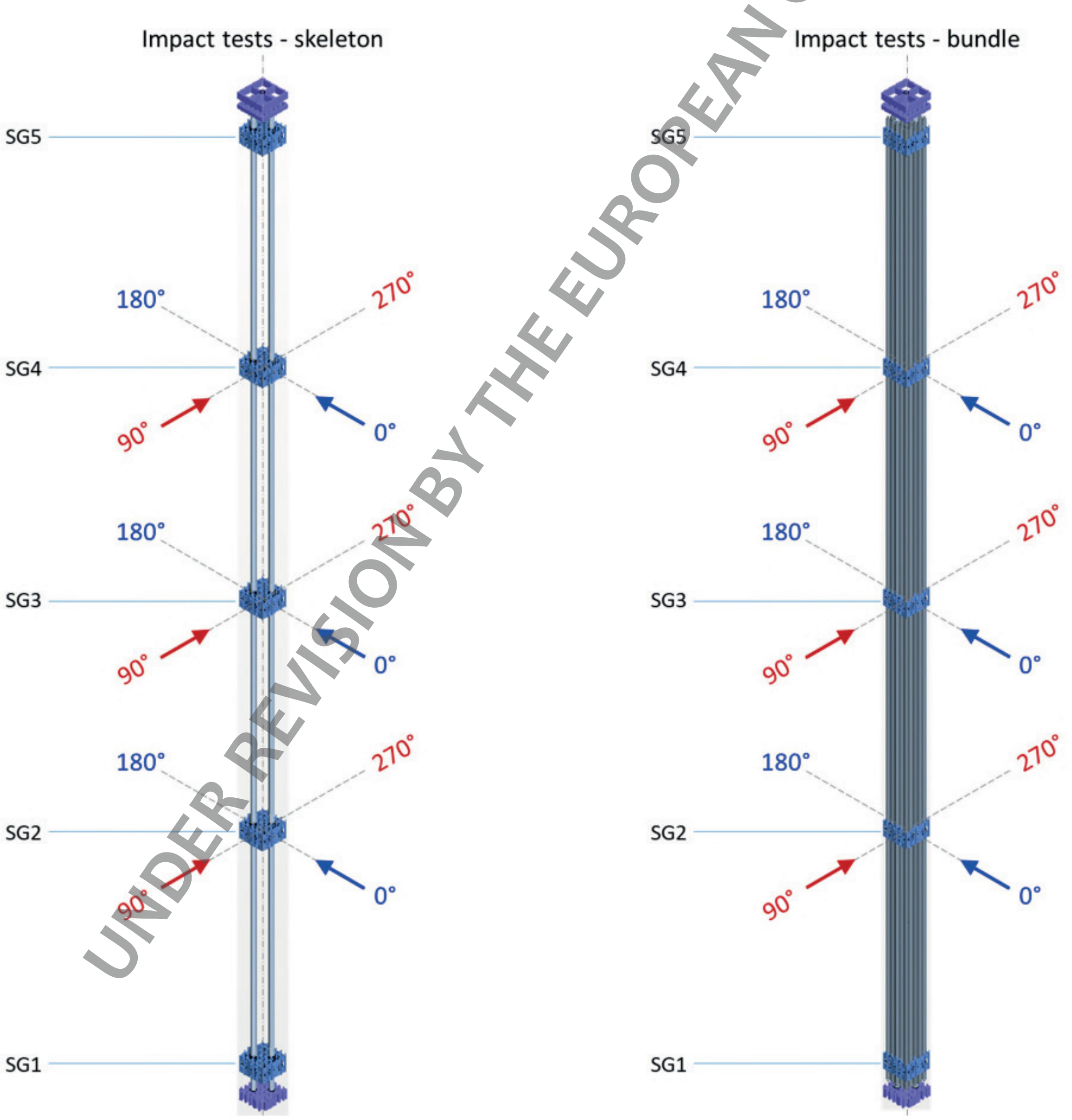

Figure 7: Setup for impact test

3.5.2 Flow tests

Flow tests were carried out at nominal medium temperature of 40°C and the nominal absolute pressure at the inlet to the test section of 4 bar.

The motion of the test bundle was investigated for different axial mean velocities in the test channel in the range between 4.0 to 7.0 m/s. The velocity was changed stepwise with a general increment of 0.2 m/s. For the velocity range between 5.0 and 5.4 m/s a finer increment of 0.1 m/s was applied. For the use within GO-VIKING project the data set obtained for average axial velocity $\langle \mathrm{w} \rangle = 5.2\ \mathrm{m/s}$, for which also the flow field LDA measurements were performed, will be provided.

Motion of the whole bundle was measured at three levels (SG2, SG3, SG4) in two lateral directions (0°-180° and 90°-270°), see Figure 8. For investigations of rod vibration one representative rod was chosen. Rod motions were measured in two directions at two elevations[1]: mid-span between SG1 and SG2 (level I) and mid-span between SG3 and SG4 (level III).

The vibration measurements were performed for a duration of 600 s with a sampling frequency f_s of 500 Hz.

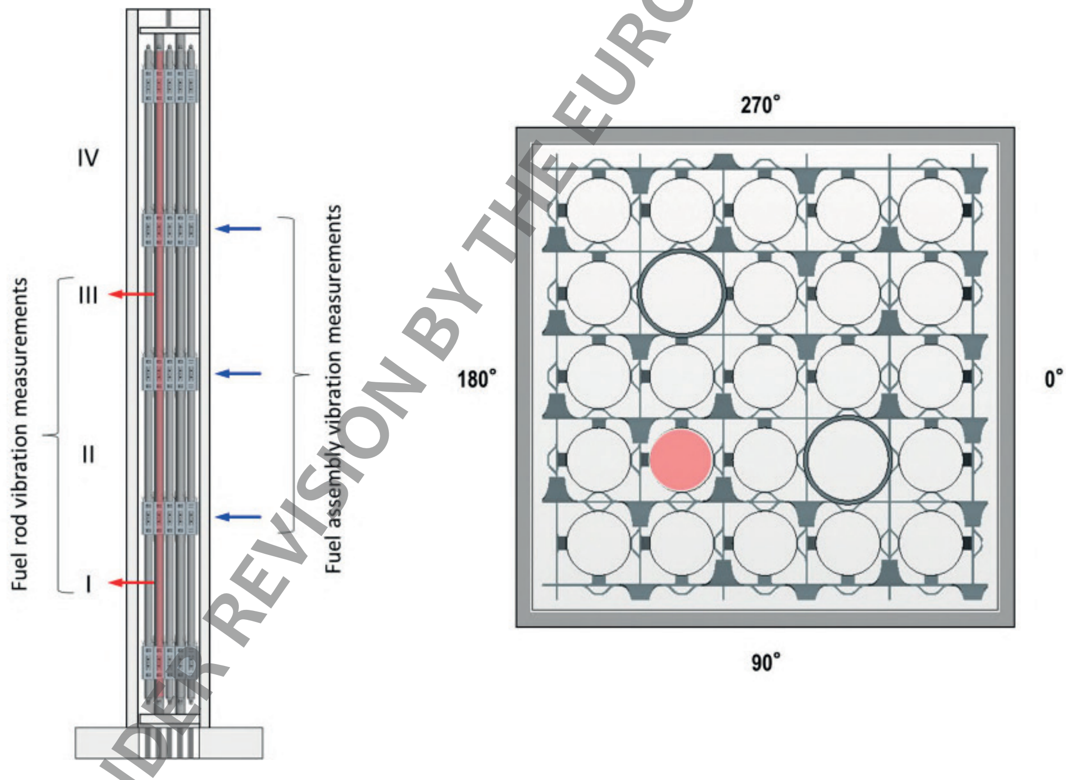

Figure 8: Planes for vibration measurements of the fuel assembly and fuel rod

LDA measurements were carried out at five different elevations downstream the second spacer grid. At each elevation the flow field profiles were measured along two lines (traverses) located in the middle of the flow sub-channels next to the central rod row as indicated in Figure 9. The LDA measurements were performed for the flow rate corresponding to mean

[1] The rod vibration measurements were not measured at both elevations in all tests.

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velocity of 5.2 m/s within the test channel. Reynolds number for this flow rate based on the average axial velocity and hydraulic diameter of 11.2 mm of the flow cross-section within the tests channel in the rod bundle area is 88,500.

During tests, axial velocity component parallel to main flow (z direction in Figure 9) and horizontal velocity component perpendicular to profile line (y direction in Figure 9) were measured separately as a function of the distance to the wall of the test channel (x coordinate in Figure 9). The axial velocity component was generally measured over the whole width of the channel. Due to spatial limitations, the horizontal velocity component was measured only up to 25 mm from the reference channel wall. The step between measurement points in both cases was 1 mm. Measurement duration for evaluation of the mean flow velocity was limited either to 20 s or 30,000 measurement points (samples). For estimation of the mean velocity $\bar{u}$ and the velocity root mean square (RMS) u_{RMS}, weighting technique was applied:

$$\bar{u} = \sum_{i=1}^{N} u_i \cdot w_i \Big/ \sum_{i=1}^{N} w_i \tag{6}$$

$$u_{\mathrm{RMS}} = \sqrt{\sum_{i=1}^{N} (u_i - \bar{u}_i)^2 \cdot \mathrm{w}_i \Big/ \sum_{i=1}^{N} \mathrm{w}_i} \tag{7}$$

where N represents the number of samples, u_i the discrete value of the velocity measured at time t_i, and w_i is a weighting factor. As a weighting factor, the inter-arrival time Δt ($\mathrm{w}_i = \Delta t_i$) in backward mode ($\Delta t_i = t_i - t_{i-1}$) is used. More details on LDA data processing and procedures can be found in Nobach (1999).

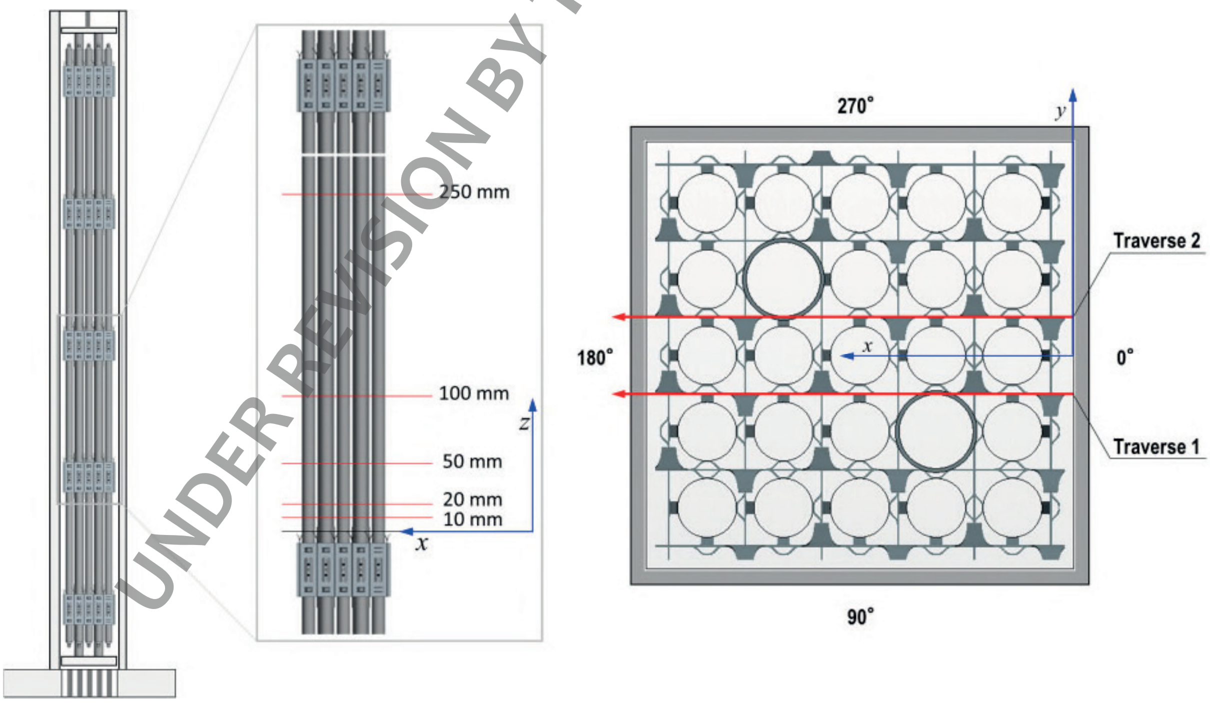

Figure 9: Planes for LDA measurements

4. Test results

4.1 Impact tests

Natural frequencies of the test bundle were determined utilizing impact test. Both the skeleton and the complete bundle were investigated. The response of the test bundle and the skeleton to the applied impact was measured at the surfaces of spacer grids. The results of spectral analysis of the displacement time histories at spacer grid positions measured during impact tests are presented in Appendix 1. Natural frequencies that can be identified from the plots are summarized in Table 6.

Natural Frequency / Mode →		1	2	3	4	5	6
Skeleton	0°-180° (x)	9.1	16.0	23.9	34.4	44.3	51.15
	90°-270° (y)	8.8	15.8	23.55	34.1	43.9	50.8
Bundle	0°-180° (x)	6.0	14.4	23.9	-	-	-
	90°-270° (y)	6.0	14.5	23.9	-	-	-

Table 6: Overview of natural frequencies for skeleton and fuel assembly

4.2 Flow-induced vibration tests

The main purpose of the FIV tests was to investigate the sensitivity of fuel assemblies equipped with specific spacer grid designs to flow-induced vibration. The results of the FIV tests, performed for the conditions corresponding to 5.2 m/s average axial velocity are presented in Appendix 2. The results are provided in terms of power spectral density (PSD) of corresponding displacements of spacer grids 2, 3 and 4, and of a fuel rod at mid-span position between spacer grids 1 and 2 measured during FIV tests. The PSD plots provide evidence about dominant frequencies of bundle vibration response induced by fluid flow at given conditions. The most dominant frequencies are around 5-6 Hz and around 12-12.5 Hz, corresponding to first and second natural frequencies measured by impact tests (see section 4.1). The second dominant frequency (12-12.5 Hz) is strongly pronounced only at spacer grids 2 and 4. The vibration amplitude seem to be slightly higher at spacer grid 4 compared to other two positions, but it is generally at very low level below 10 µm RMS. This is, however, a typical vibration amplitude measured also for full-scale fuel assemblies at comparable flow conditions. Such small amplitudes are usually associated with turbulence-induced vibration. In the PSD plot derived from the measured displacement for a fuel rod the most dominant frequency is in the range 60-70 Hz corresponding to first natural frequency of the fuel rod clamped in the spacer grid cells. The peaks at low frequency range correspond to vibration frequencies of test bundle.

4.3 Results of LDA measurements

The results from LDA tests are summarized in Appendix 3. The results are provided in terms of profiles of mean and RMS fields of axial $\langle w \rangle$ and horizontal $\langle v \rangle$ velocity components along two lines across the cross-section and at several axial locations behind second spacer grid according to description in section 3.5.2. Flow tests were carried out under constant inflow conditions for an average axial velocity in the test channel of 5.2 m/s.

5. Data files

In this section the list of data files accompanied with this report is provided. Data file lists are provided for the CAD data of the fuel assembly model as well as for each type of tests separately in the following subsections. The CAD model of the test fuel assembly is provided in para-solid format and it is optimized for CFD simulation.

5.1 CAD data of fuel assembly and test channel

#	Data file	md5sum
1	FuelAssemblyStructure.x_b	5cdc158d0db8249a477c1e562aa8f594
2	TestChannel.x_b	e922f7721b08af3290caa0b4b0670fa6

5.2 Data files from impact tests

#	Data file	md5sum
1	d2p3_impactTest_V082_Skeleton_impactSG2_x.dat	f98d88f287d3badc60ad5763c443ac71
2	d2p3_impactTest_V083_Skeleton_impactSG3_x.dat	df213571195aeb51db4eea7103b54366
3	d2p3_impactTest_V085_Skeleton_impactSG4_x.dat	564b0970d0bcdbfdd2b947e060350d8c
4	d2p3_impactTest_V086_Skeleton_impactSG2_y.dat	1c0d6e17c0d5c3fb86573cde8a346a69
5	d2p3_impactTest_V087_Skeleton_impactSG3_y.dat	c7fbf6f241517ebb383026fb44385b40
6	d2p3_impactTest_V089_Skeleton_impactSG4_y.dat	c71fe6b0e85a77d5850780c637bc1cea
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5.3 Data files from FIV tests

#	Data file	md5sum
1	d2p3_fiv_V326_w5p2mps.dat	2b80b7d5adaecba7d62e415c3fe476d8

5.4 Data files from fluid flow LDA tests

#	Data file	md5sum
1	d2p3_lda_axialVel_T1_z010mm.csv	c20ea3af9963e3880a156bcfb5bd3b8f
2	d2p3_lda_axialVel_T1_z020mm.csv	a235e3036513b60be447437d71bea4ea

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3	d2p3_lda_axialVel_T1_z050mm.csv	7feb7e9f84d72a23b4857121734d391b
4	d2p3_lda_axialVel_T1_z100mm.csv	553aec3d7425d8b3a1dbedd9ca622df4
5	d2p3_lda_axialVel_T1_z250mm.csv	d0a0ef9004e96f7fc58ba9392e567600
6	d2p3_lda_axialVel_T2_z010mm.csv	882e4a026ff1b88c86f42786f87e72d1
7	d2p3_lda_axialVel_T2_z020mm.csv	50c845b4e69e51f5ae1eced21de1893d
8	d2p3_lda_axialVel_T2_z050mm.csv	4f30128ea2b5a0e37b419211f1ef201
9	d2p3_lda_axialVel_T2_z100mm.csv	0092717919f144a79a56c0275a75ad21
10	d2p3_lda_axialVel_T2_z250mm.csv	c0a412ca74762b98a1f3b69a7b54cbe3
11	d2p3_lda_horizVel_T1_z010mm.csv	f01000a19cf6aebacf0b93e3621a4c42
12	d2p3_lda_horizVel_T1_z020mm.csv	ba89ef56de87addf3d8fcddc178398a5
13	d2p3_lda_horizVel_T1_z050mm.csv	e14b72b8bfef986ea50e1030d49f90d7
14	d2p3_lda_horizVel_T1_z100mm.csv	0465a5499f50c137fe99443514ea7300
15	d2p3_lda_horizVel_T1_z250mm.csv	36b3ebd400bafd133b178d363f5708b4
16	d2p3_lda_horizVel_T2_z010mm.csv	76216294161191e2e34fc9204a335a17
17	d2p3_lda_horizVel_T2_z020mm.csv	6b745588c4798682d535653d371cfef2
18	d2p3_lda_horizVel_T2_z050mm.csv	8784ab85f8ec8e6ee40b08d5ec8b0efd
19	d2p3_lda_horizVel_T2_z100mm.csv	78fe4469edd7791fa7e3be04f0e3fdbc
20	d2p3_lda_horizVel_T2_z250mm.csv	58ccc87e58ab77384ce372989c6ce59e

6. Benchmark setup and objectives

The experimental setup described in this document serves as the basis for the setup of the numerical simulations of Benchmark 2 of the WP2. The envisaged numerical simulations include fluid flow and structural mechanics analyses.

For the fluid flow simulations, the numerical setup has to reflect the following global flow boundary conditions used in the tests:

- Fluid flow is considered as incompressible.
- Fluid properties are derived from the operating conditions in the test:
    - Temperature $T = 40°\mathrm{C}$ and absolute pressure $p_{\mathrm{abs}} = 4$ bar.

  According to H_2O IAPWS-IF97, the corresponding fluid properties of water to be used in simulations are:

    - Density: $\rho = 992.355\ \mathrm{kg/m^3}$
    - Dynamic viscosity: $\mu = 6.5277 \cdot 10^{-4}\ \mathrm{Pa\ s}$

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- Mass flow rate corresponding to average axial velocity $\langle w \rangle = 5.2\ \mathrm{m/s}$ in the test channel cross-section in the pure bundle area[2] :
  - $\dot{m} = 14.996\ \mathrm{kg/s}$
- The geometry of the fluid flow domain is defined by the CAD models of the fuel assembly structure and of the test channel which are a part of the deliverable.

For the structural model following global input parameters are to be used:

- Mass of different components given in Table 3 and properties of corresponding materials given in Table 2
- Depending on the modelling strategy for structural model, the following boundary conditions are to be used:
  - fully clamped boundary conditions for guide tubes or whole bundle at bottom and top end (zero displacements and zero rotations)
  - clamping force of 20 N for the fuel rods inside spacer grids

Independently of the modelling strategy, structural models have to be able to reproduce the results of the impact tests in terms of vibration response in frequency domain.

The objectives of the numerical simulations within the Benchmark 2 of WP2 are:

- Evaluate vibration behaviour of the bundle based on simulations results and compare with the experimental data in terms of:
  - RMS displacement at spacer grid positions 2, 3 and 4 (quantitative evaluation),
  - Vibration response frequency spectrum at spacer grid positions 2, 3 and 4 (qualitative evaluation)
- Evaluate flow field within bundle based on simulation results and compare with experimental data in terms of:
  - Mean velocity profiles
  - RMS velocity profiles

  along the profile lines and at axial elevations as explained in section 3.5.2 (Figure 9)

- In addition to the above described comparison with experimental results, the fluid forces exerted on the fuel assembly need to be evaluated (monitored) in CFD simulations[3] and compared between different simulation approaches. The way how the fluid forces need

[2] Test channel cross-section area reduced by the cross-section area of all rods and guide tubes
[3] As stand-alone or as a part of coupled FSI simulation

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to be monitored in simulations will be defined later before the start of numerical simulations activities.

7. Conclusion

This report provides the experimental data from the FIV tests with reduced 5x5 fuel assemblies performed by Framatome according to definition of the GO-VIKING deliverable D2.3. In this context, the document provides a description of the test setup, test fuel assembly, boundary conditions, measuring techniques, test parameters and a compilation of the experimental results aimed to be used in the frame of the GO-VIKING project.

The data files containing the results of the tests as well as the files containing the geometry of the test setup (fuel assembly) are provided separately as a part of the deliverable D2.3. The data provided by this deliverable will be used for validation of numerical simulation approaches dedicated to addressing the FIV in fuel assemblies to be developed within the WP2 of the GO-VIKING project. The configuration investigated in the experimental studies described in this report form the basis for the Benchmark 2 of the WP2.

This benchmark will contribute to achievement of the overall GO-VIKING project objectives through development of simulation methods and improvement of understanding of FIV phenomena in fuel assemblies. This expectation is particularly supported by the benchmark configuration, which incorporates all relevant features of a real PWR FA, thus reflecting realistically the FA operating conditions.

8. Bibliography

Durst, F, Melling, A, Whitelaw, JH (1976). Principles and Practice of Laser-Doppler Anemometry. Academic Press, London, 1976

Albrecht, H-E, Borys, M, Damaschke, N, Tropea, C (2003). Laser Doppler and Phase Doppler Measurement Techniques. Springer, 2003

Nobach, H (199). Processing of Stochastic Sampled Data in Laser Doppler Anemometry. Proc. of the 3rd International Workshop on Sampling Theory and Applications, 11-14 August 1999, Loen, Norway, 1999

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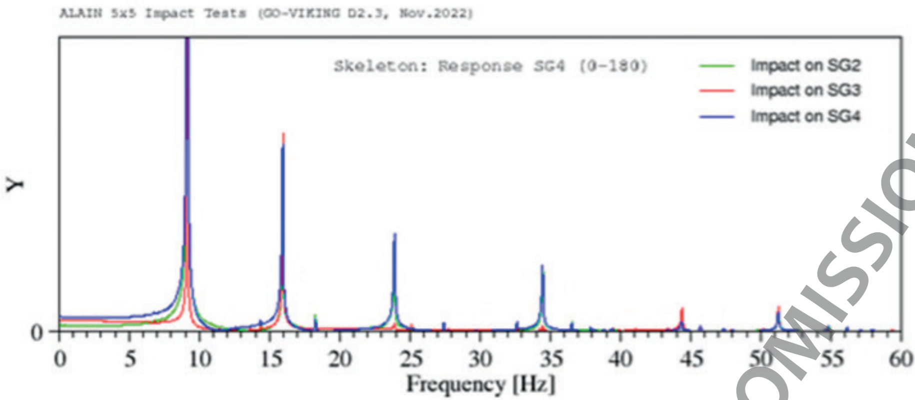
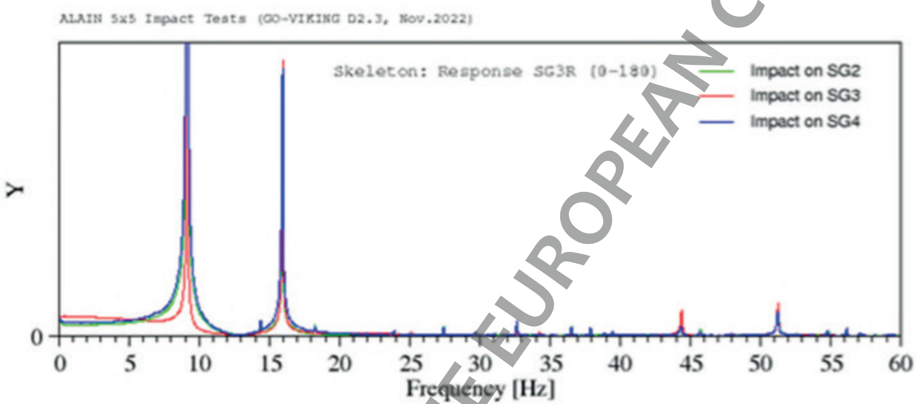
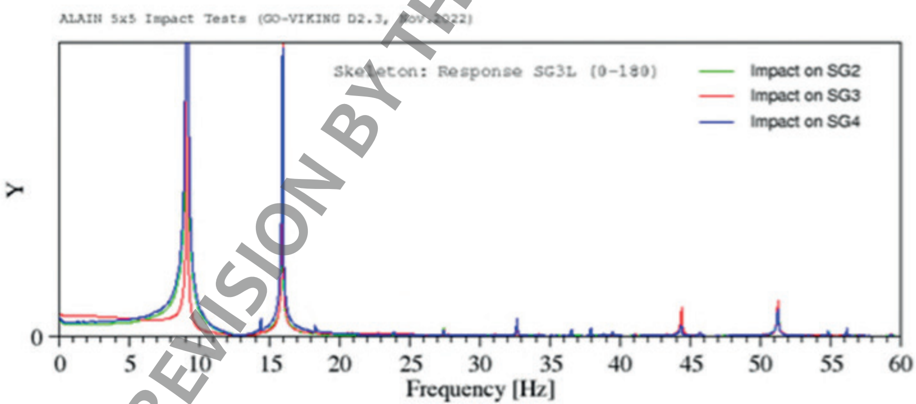
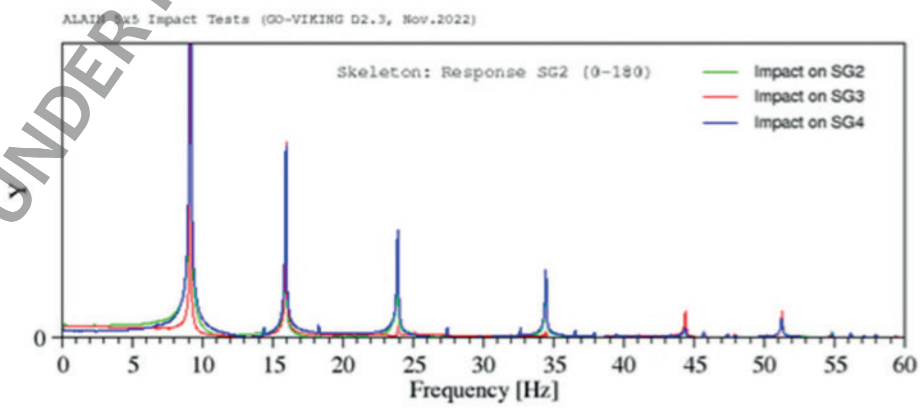
Appendix 1: Results of impact tests

Vibration response spectra – skeleton impact tests in direction 0-180°

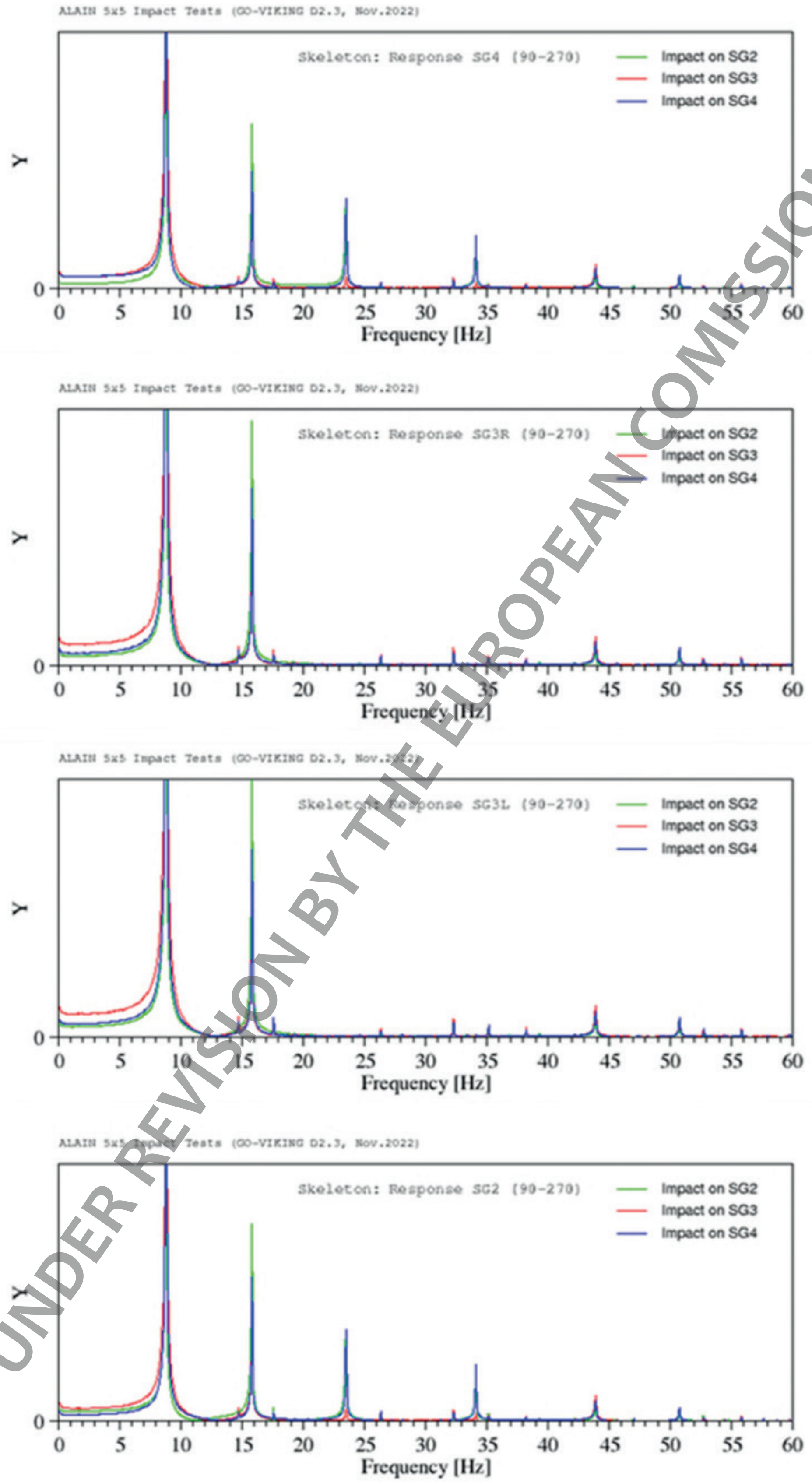








Vibration response spectra – skeleton impact tests in direction 90-270°



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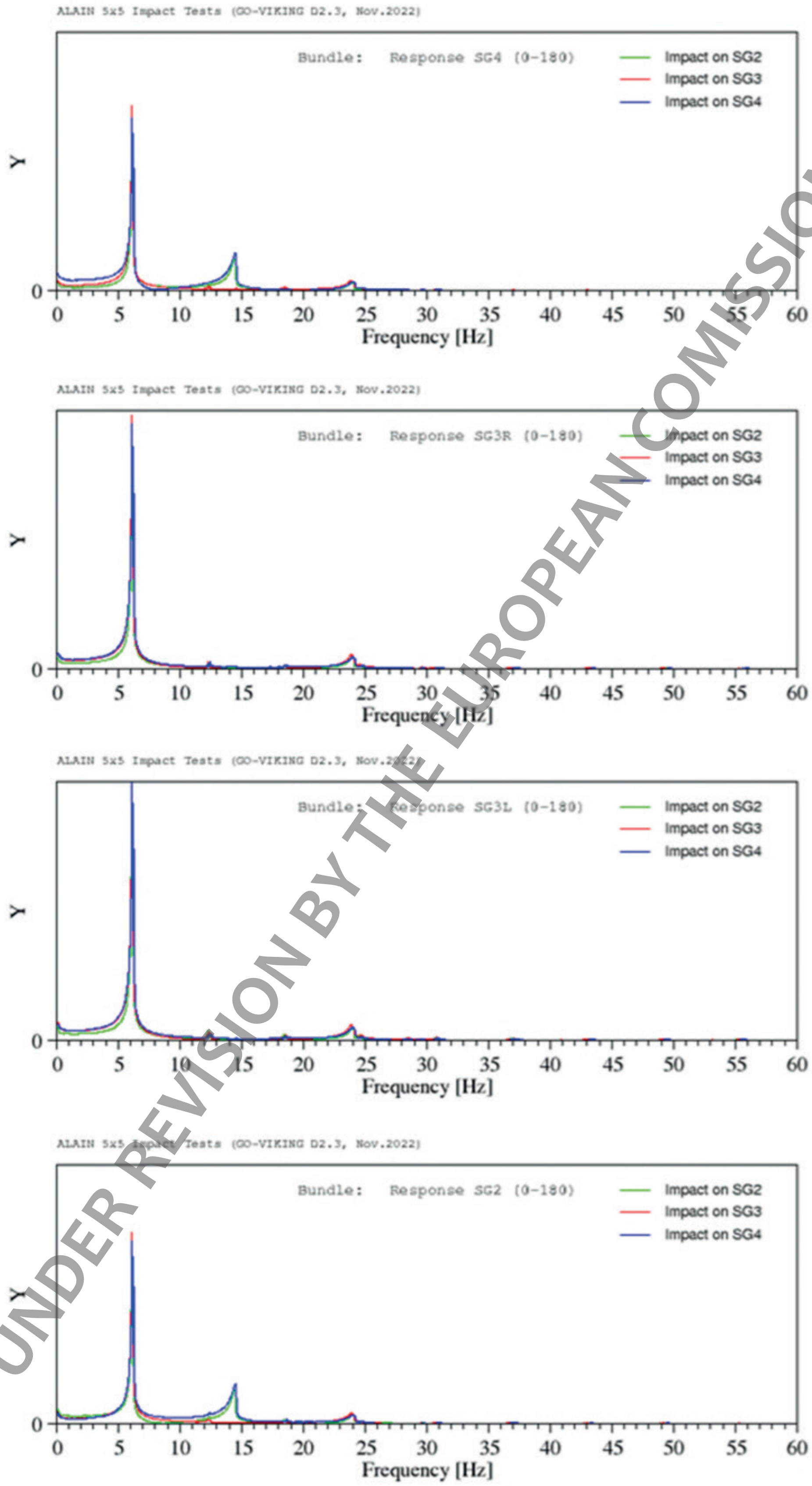
Vibration response spectra – bundle impact tests in direction 0-180°



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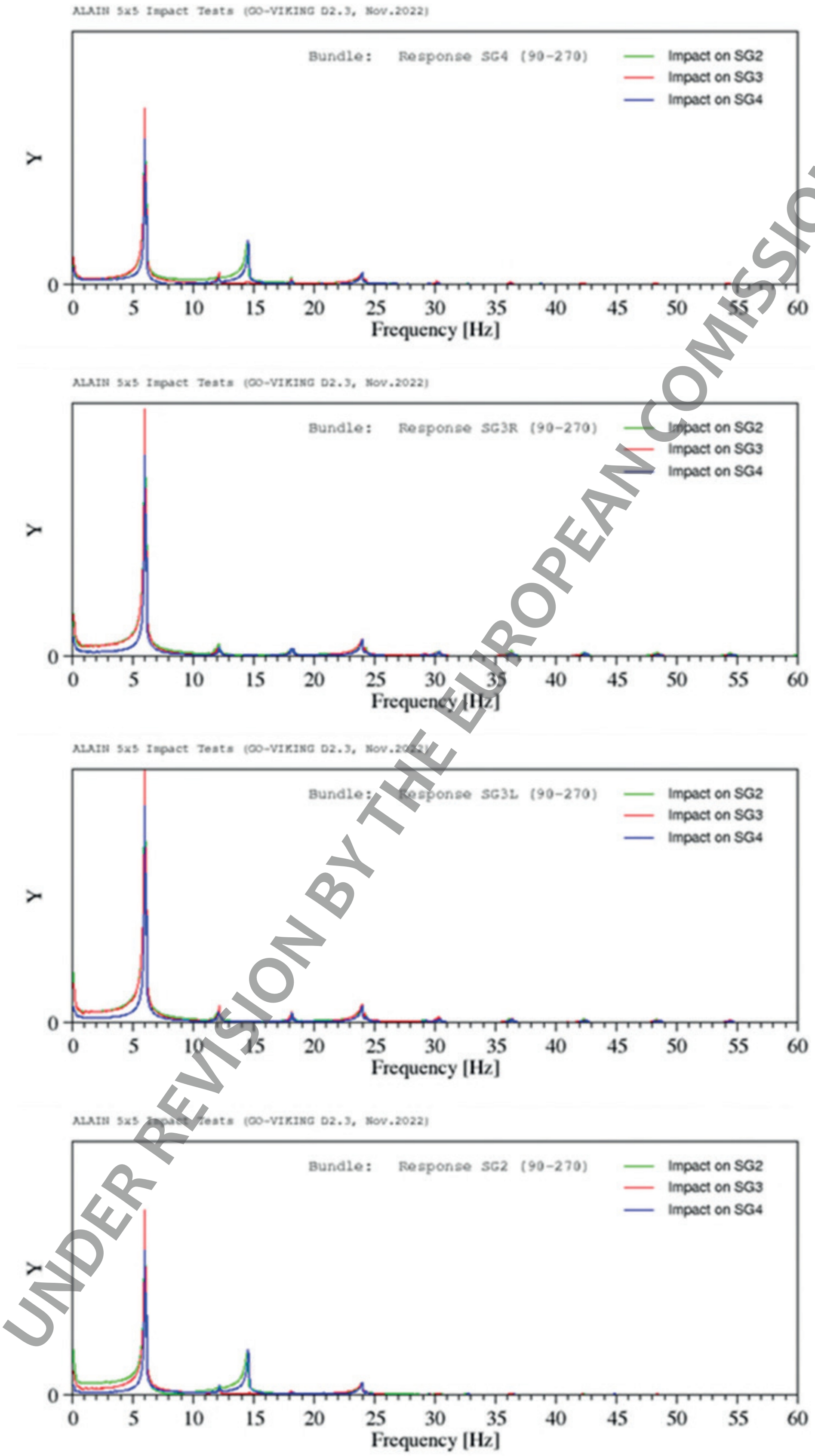
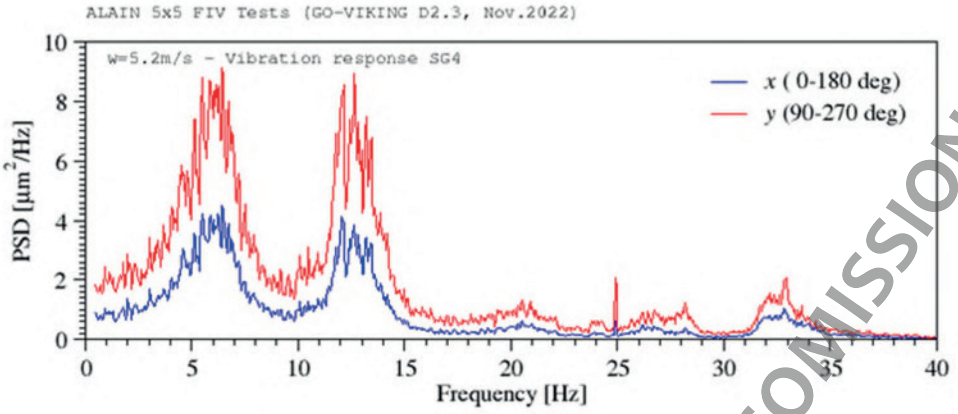
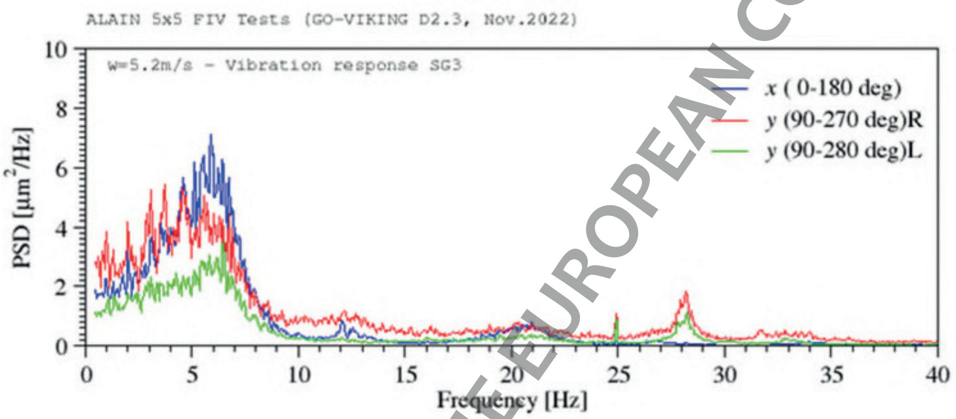
Vibration response spectra – bundle impact tests in direction 90-270°

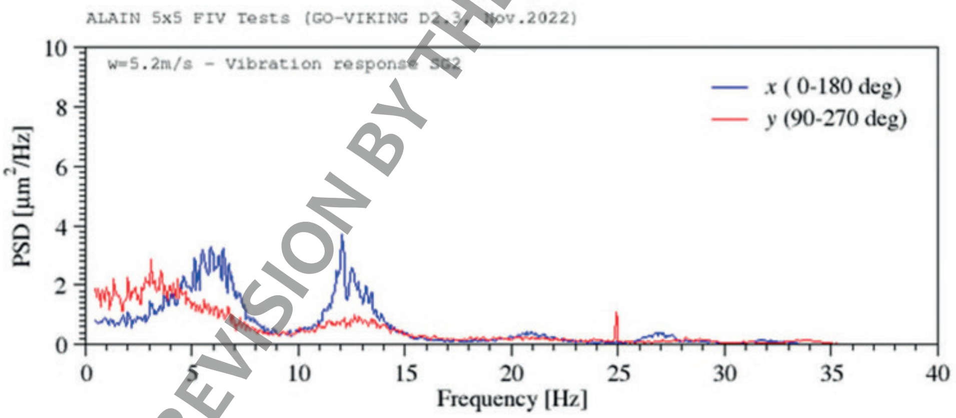


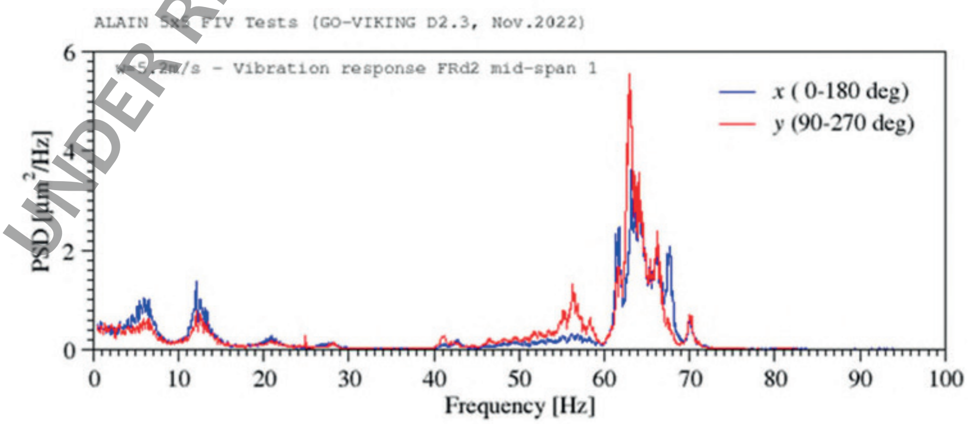
Appendix 2: Results of FIV tests

Vibration response of test bundle from FIV tests at average axial velocity $\langle w \rangle = 5.2\ \mathrm{m/s}$



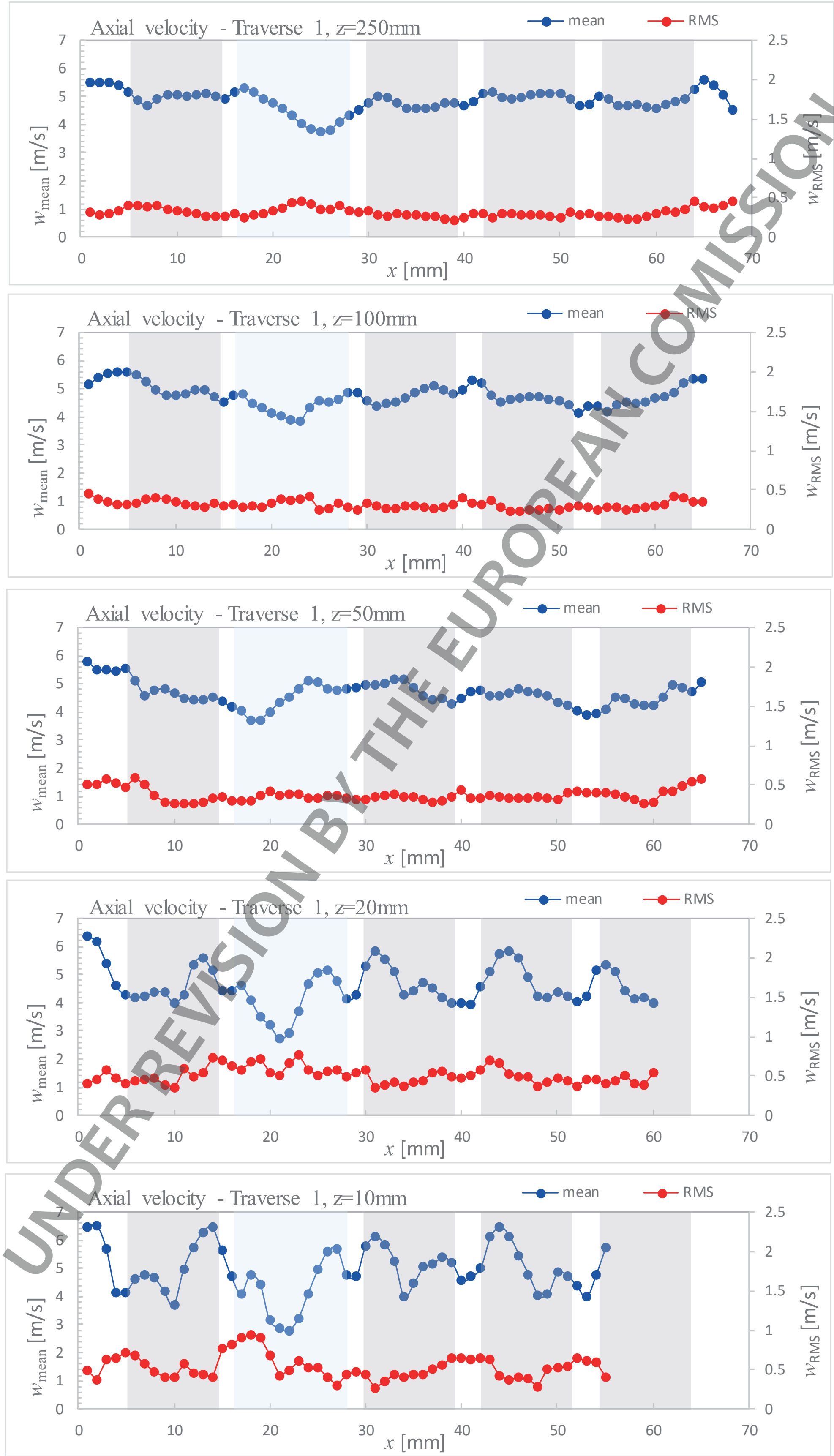




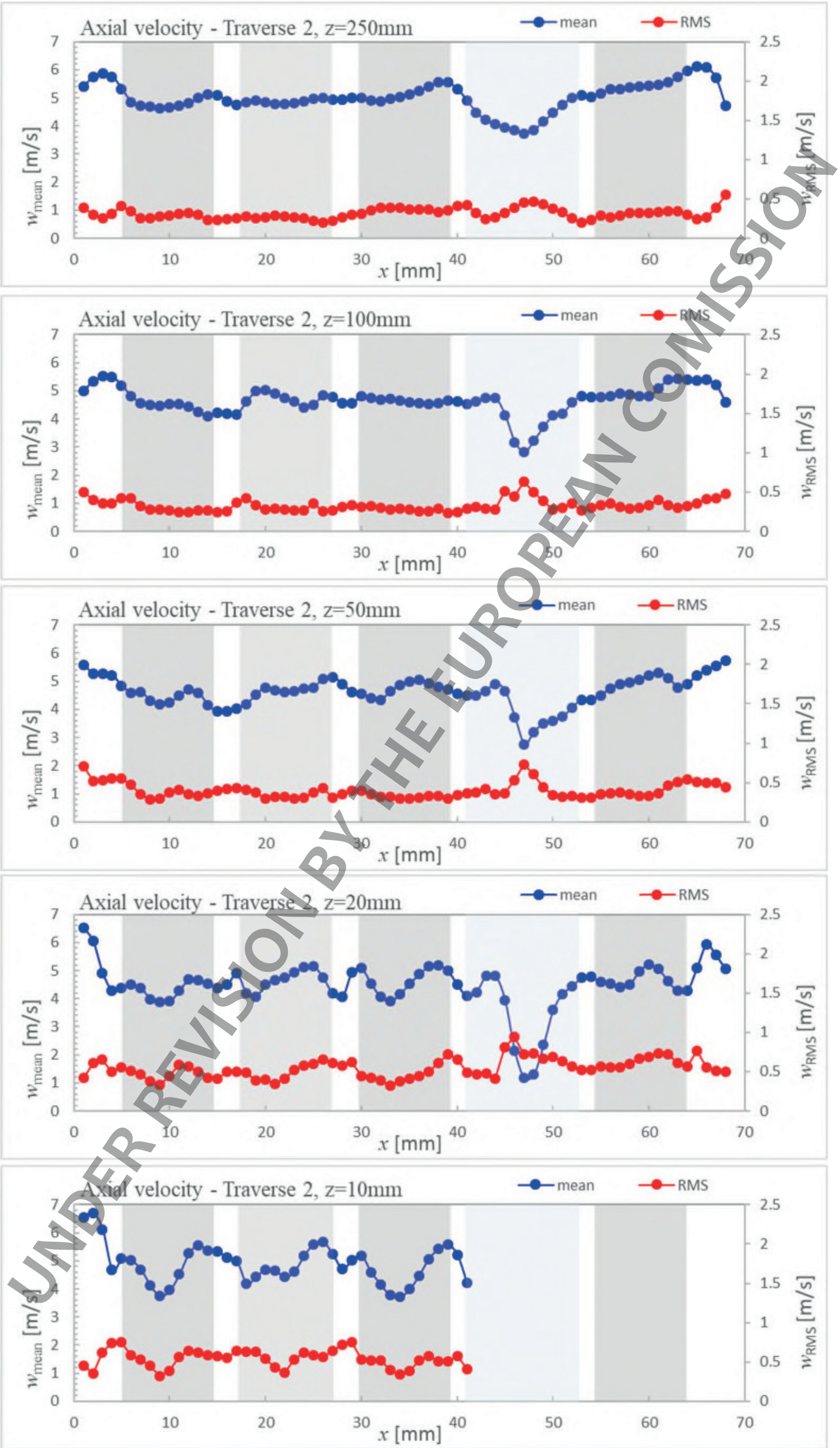


Appendix 3: Results from LDA tests - velocity profiles (cf. Figure 9)

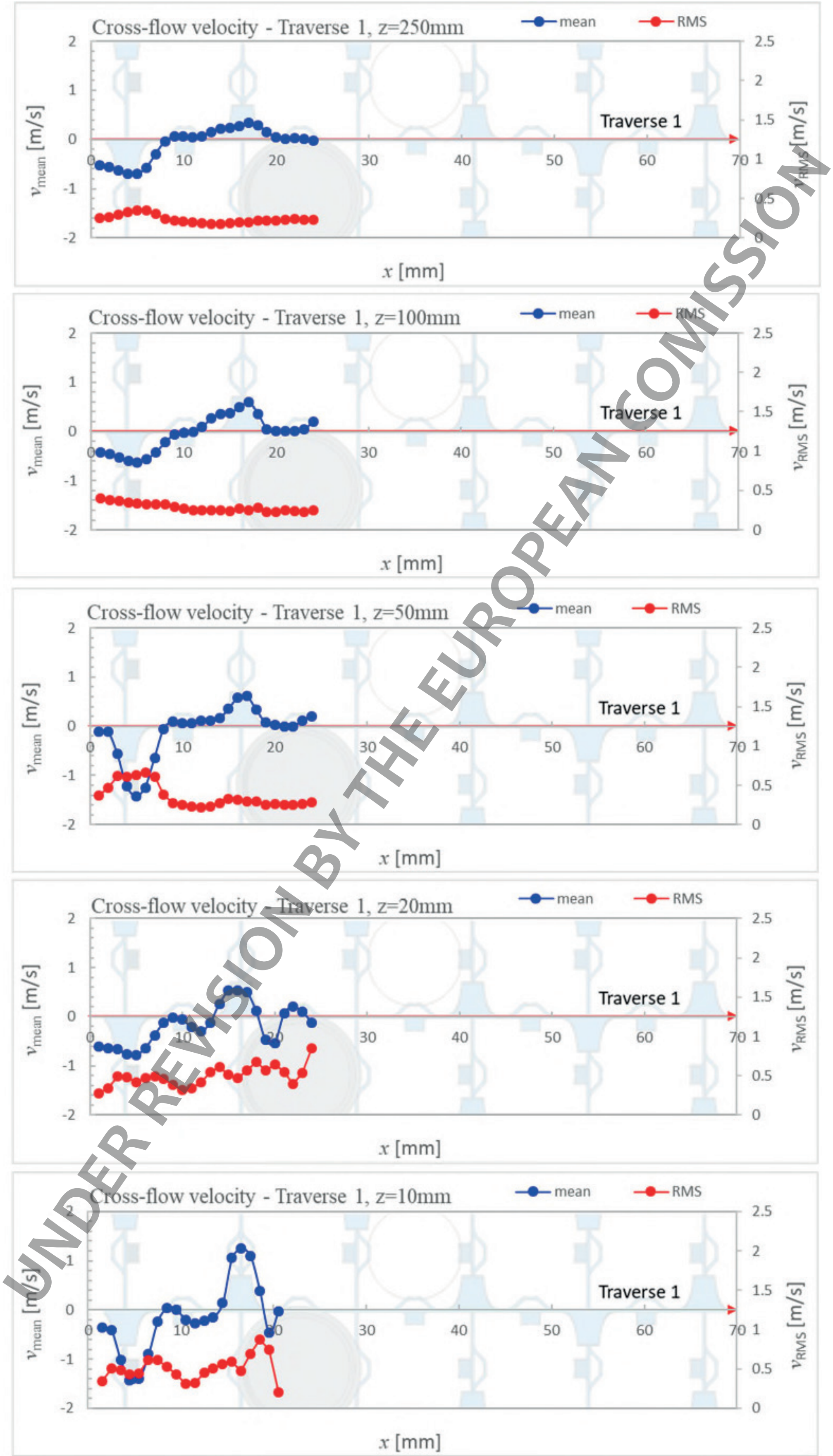
Axial mean and RMS velocity profiles along Traverse 1



Axial mean and RMS velocity profiles along Traverse 2



Cross-flow mean and RMS velocity along Traverse 1



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Cross-flow mean and RMS velocity profiles along Traverse 2