

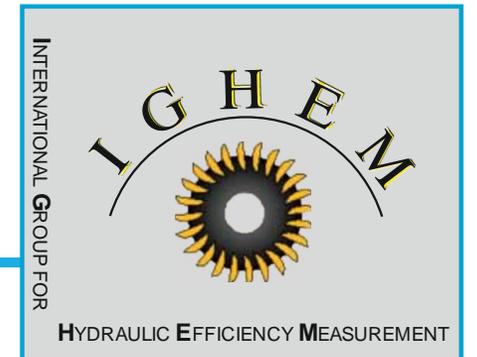


University of Belgrade, Faculty of Civil Engineering



Flow measurement methodology for low head and short intake bulb turbines Iron Gate 2 case

IGHEM2022, Grenoble, France, 03-05 October, 2022



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Flow measurement methodology for low head and short intake bulb turbines - Iron Gate 2 case

- Low head turbine → Zero or low head drop measurement
- Short intake → 2 D velocity field
- Measurements in front of trash rack → Floating gras and debris
- Iron Gate 2 specific → 3 D velocity field

Difficult situation, needs radical measures:

→ **3D EM current meters**

→ **Tailored uncertainty assessment (details in next presentation)**

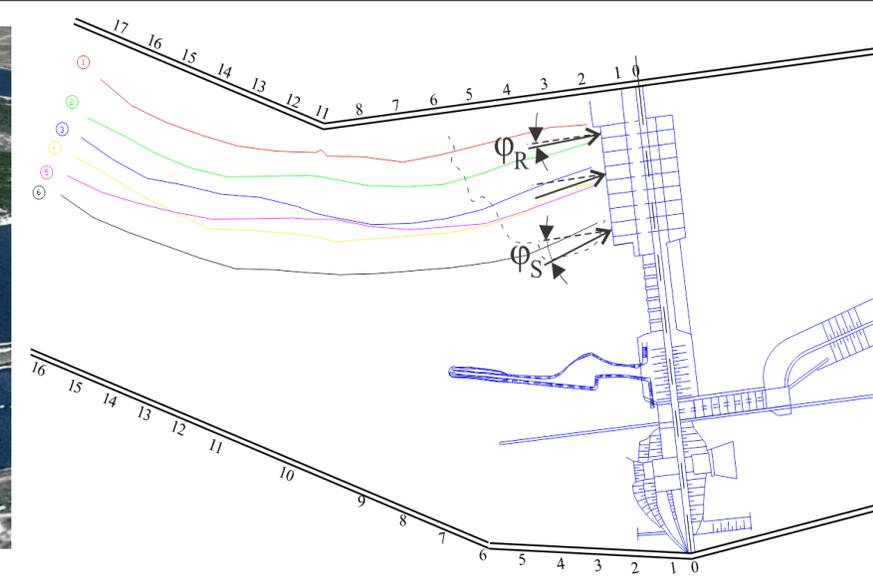
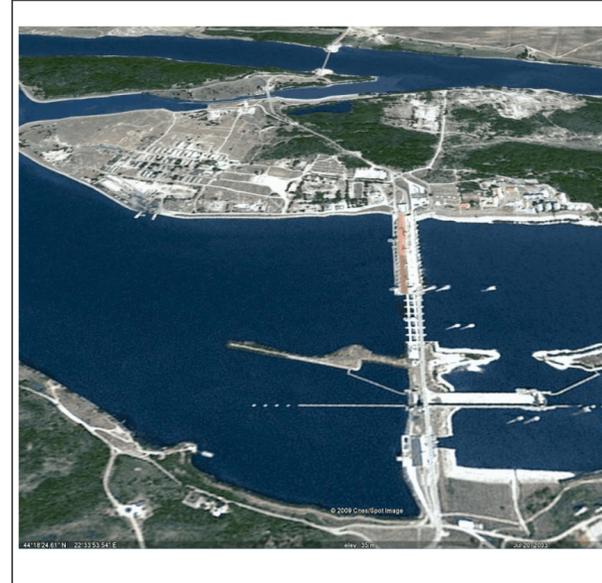




Iron Gate 2 HPP: General and specific info



- Iron Gate 2 HPP General info:
 1. Danube river
 2. **Coupled system** (w. Iron Gate 1 HPP)
 3. Total of 20 tubular (Kaplan) turbines
10 Serbian + 10 Romanian
 4. Total installed discharge 8500 m³/s



- Iron Gate 2 HPP specifics:
 1. Right bank side turbines (Serbian side) are **operating with lower hydraulic efficiency!**
 2. Physical model investigations revealed significant incident **flow angle ϕ deviations.**



Iron Gate 2 HPP: Discharge measurements

- Current situation at Iron Gate 2 HPP:
 1. Winter-Kennedy discharge measurements
 2. Calibrated (**NOT verified**) w/o φ deviations
 3. **Unknown measurement uncertainty**

↓

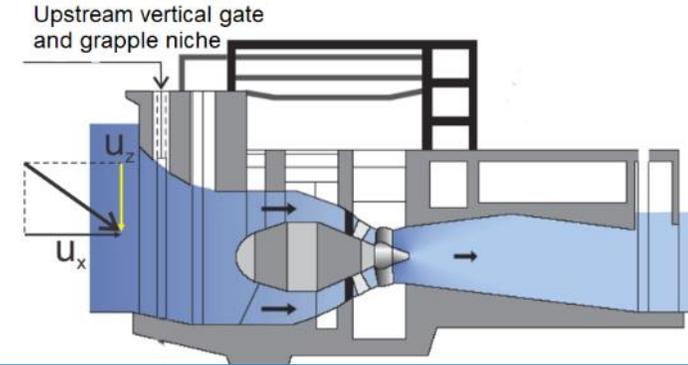
 4. **Unknown turbine hydraulic efficiency**
- Planned revitalization (Rom's finished):

↓

 5. How to calculate **turbine's efficiency gain**

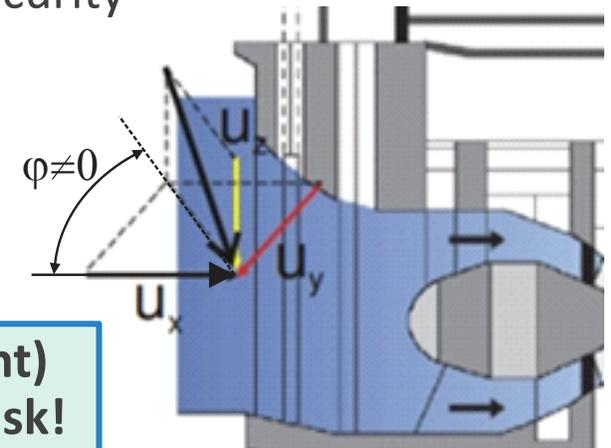
Additional (redundant) discharge measurement system is needed!

- Discharge measurement method?
 1. **Standard** (IEC 60041) methods **not applicable in short converging intakes** (tubular Kaplan)



Only **V-A method** with an array of current meters...

2. Unfortunately, stoplog gate position is **forbidden to use** due to security
3. **Current meters are not suited for angles φ higher than 15°** at entrance

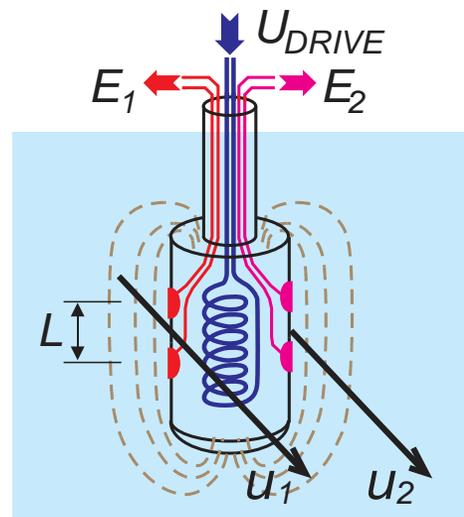
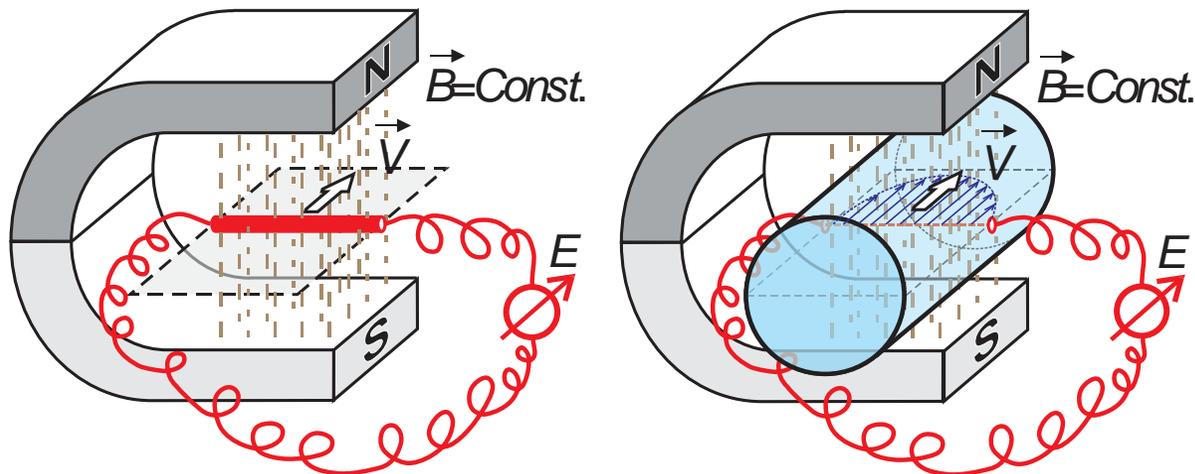


A novel **3D EM velocity** (current) meter was designed for this task!

About EM probes

- EM method for velocity measurement :
 - Method based on the **Faraday's law of induction**
 - Measures **velocity of water**, not particles
 - Mostly used for full pipe flow measurement
 - Can measure **small (mm/s)** and large velocities

- Probe can be shaped according to needs
 - Measures velocity in "point" (in small volume)
 - Can work in clean and dirty water





About EM and 2D/3D measurement



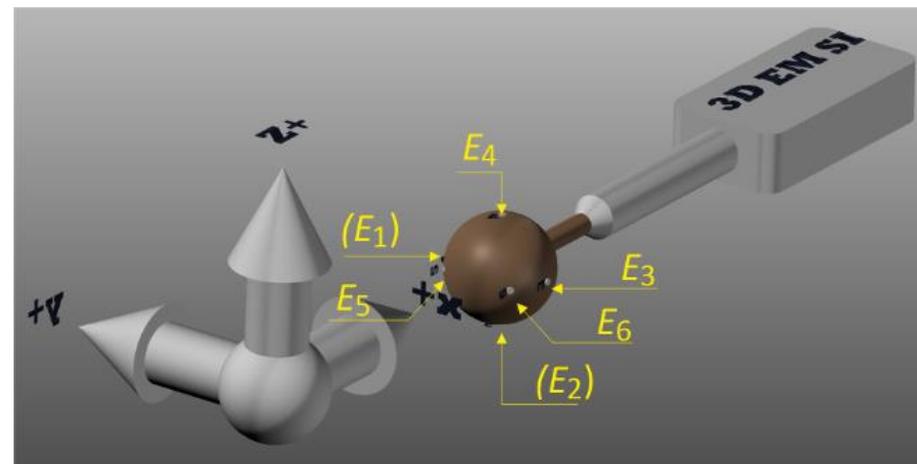
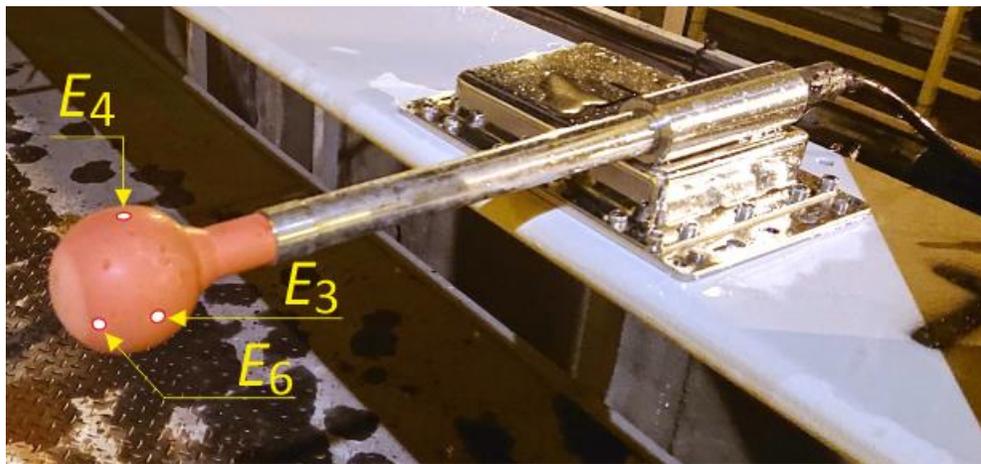
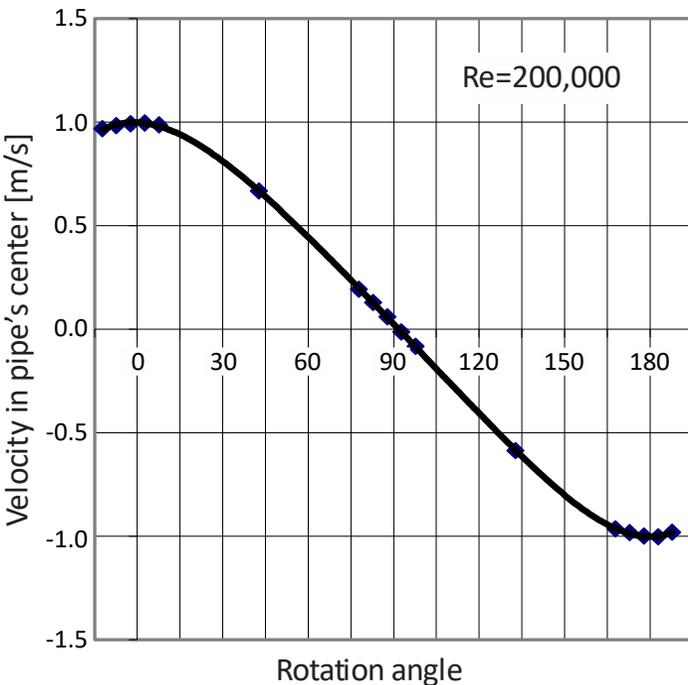
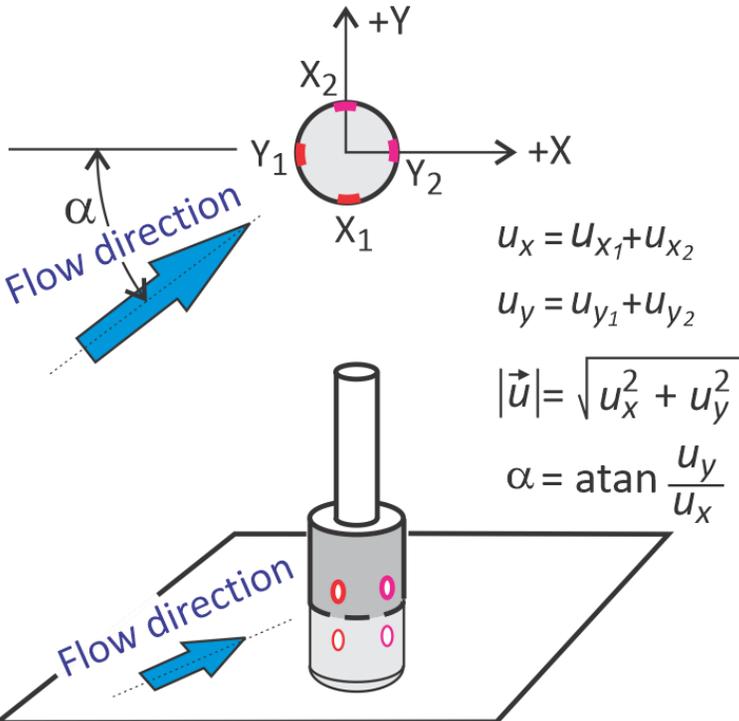
- EM method is directionally sensitive:

7. Faraday's law is **vector-based**

$$E = - \int_{\tau} (\vec{V} \times \vec{B}) \cdot \vec{j} d\tau$$

8. More electrodes to measure flow direction

- Adding more coils and electrodes we **can measure velocity in 3D**

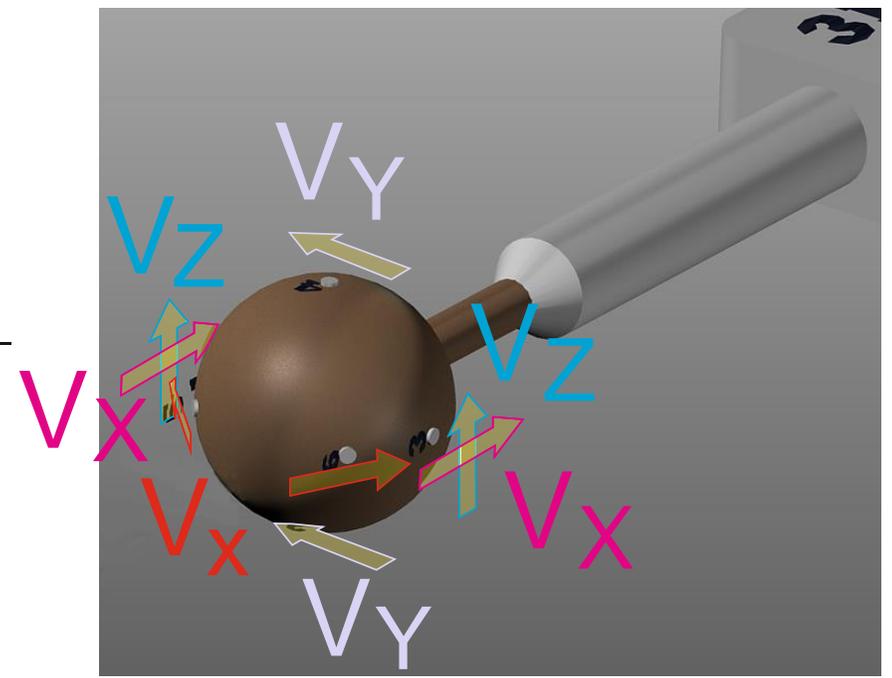
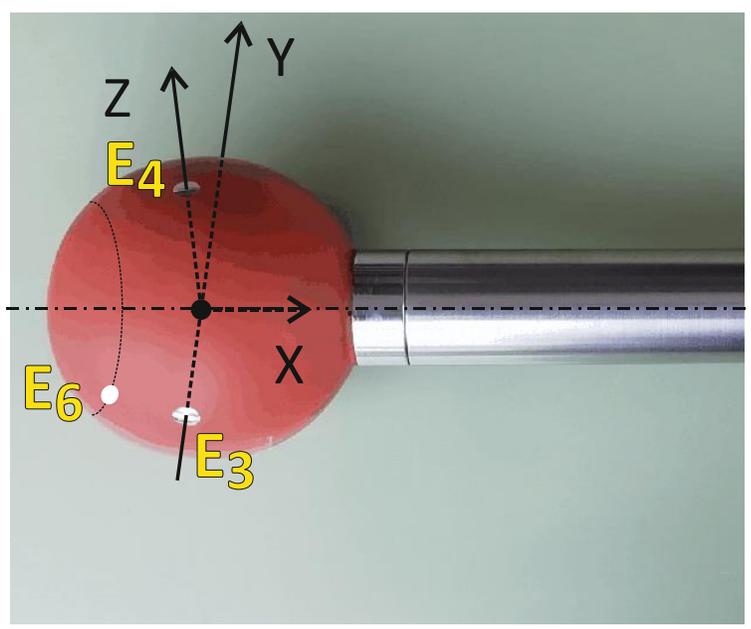
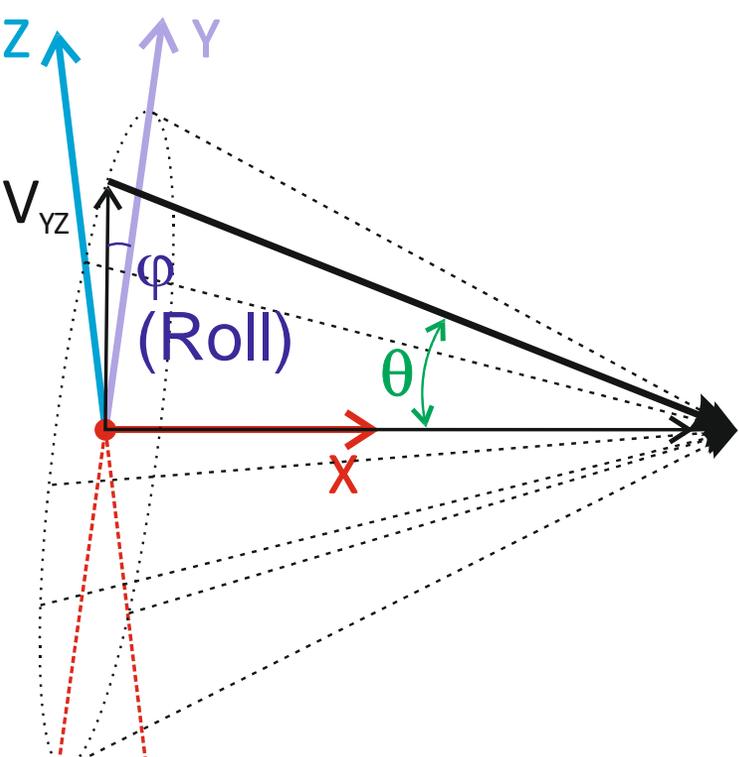




Used 3+D EM LOGxXYZ-65 probe

- 3+D EM LOGxXYZ-65 probe:
 1. Probe's head diameter 65 mm
 2. Measuring volume ~ 120 mm (like current meters)
 3. 6 electrodes, 4 independent EM sensors

- Important feature (3+D)
 4. Longitudinal X velocity component (used to compute flow) is measured twice
 5. **V_x** is **free of insertion disturbance** but more sensitive on flow angle

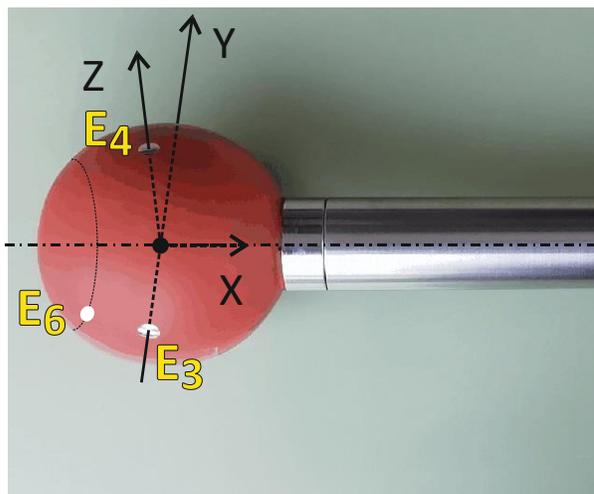
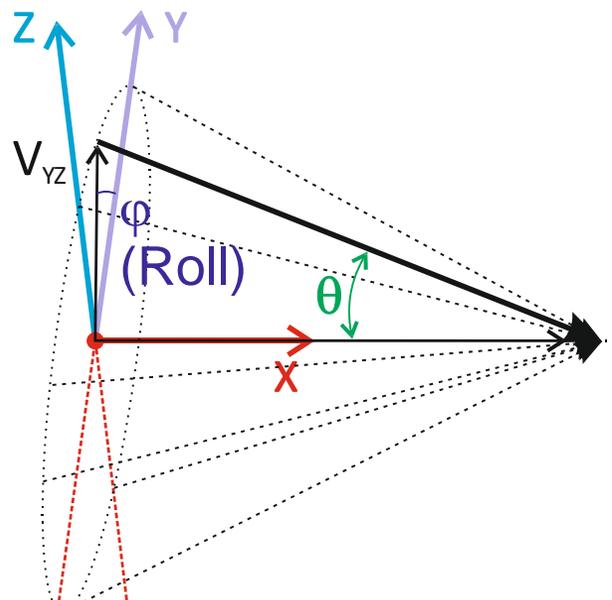
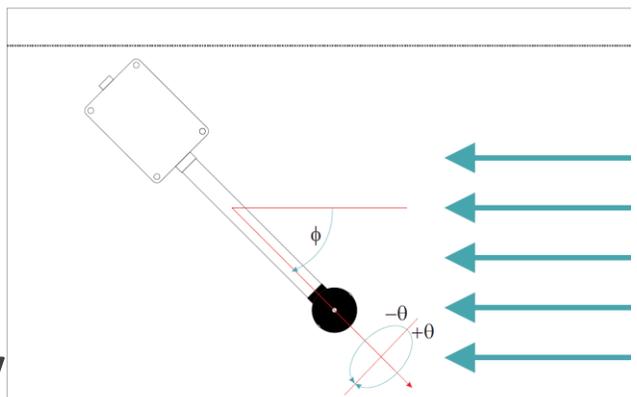




Used 3+D EM LOGxXYZ-65 probe

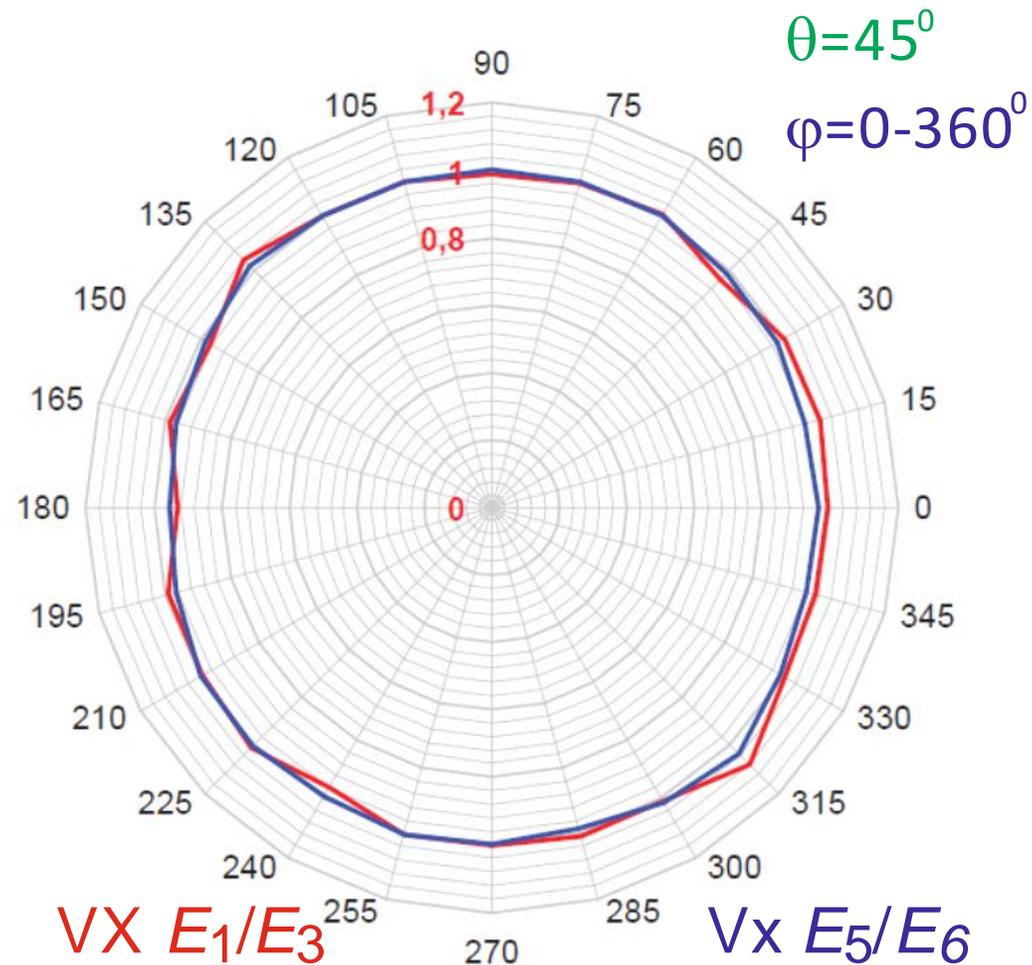
- 3+D EM LOGxXYZ-65 probe calibration:

1. In towing tank
2. **Not an easy task!**
3. Different angles used to check the angular sensitivity



- **Sensitivity** on roll angle from 0-360⁰

4. Comparison of VX and Vx



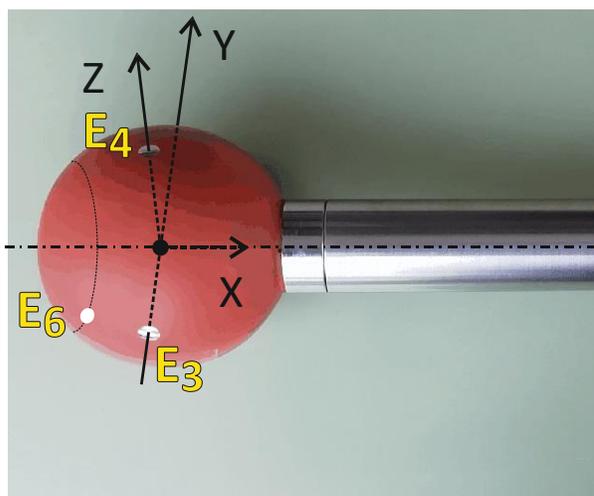
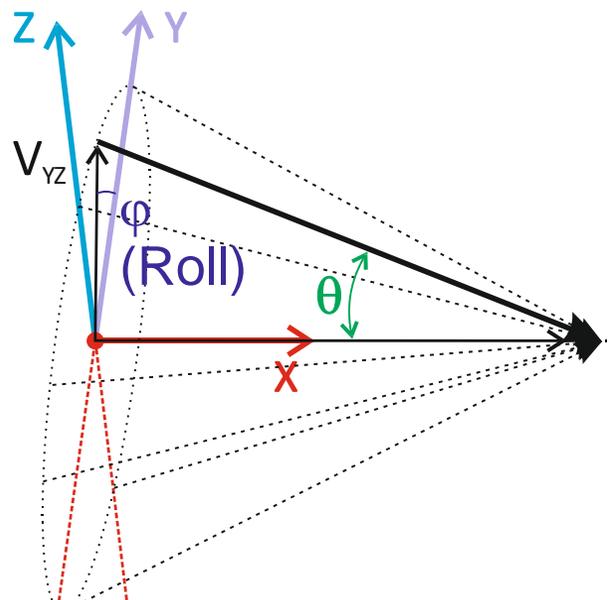
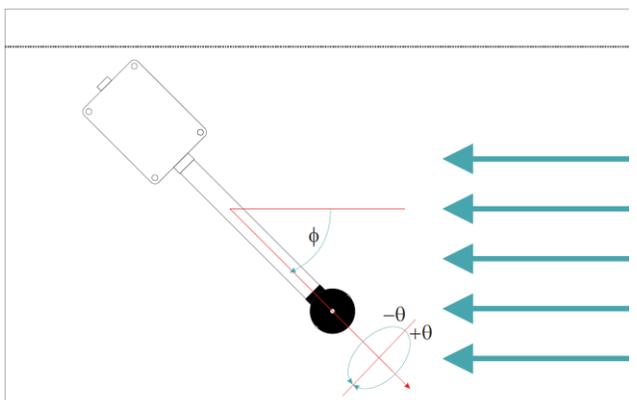


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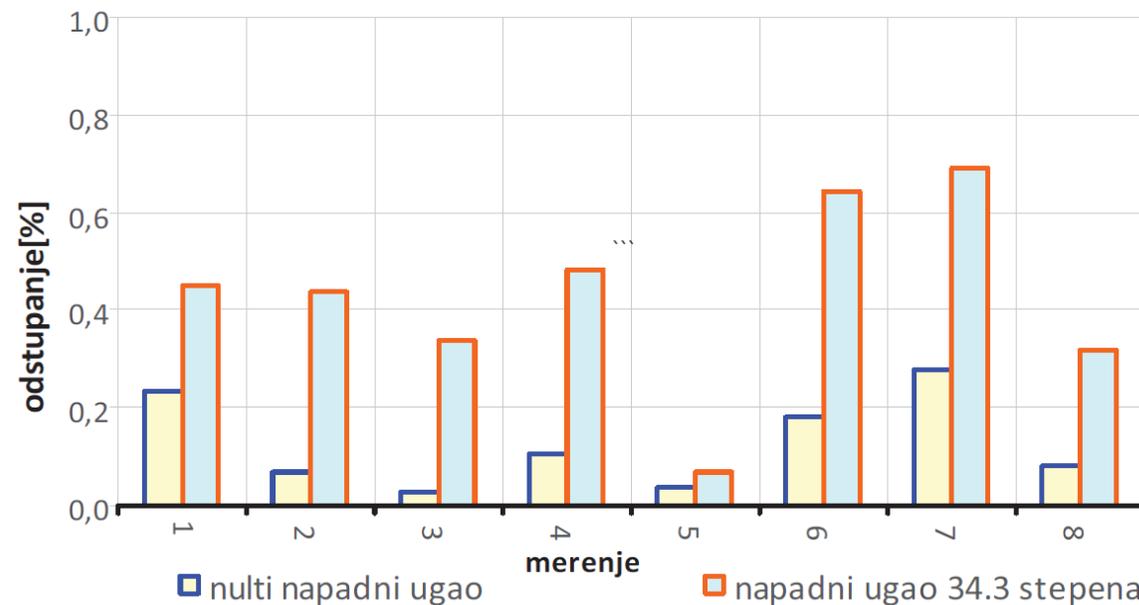


- Repeatability of V_x

5. More **suitable for small attack angles**

Ponovljivost merenja komponente V_x

-za napadne uglove 0 i 34.3 stepena ($w_z=-30, w_y=-15$),
 -test vršen na svakih 30min s brzinom $v_{ref}=1.14m/s$





3D EM and ADV as redundancy

- LOGxXYZ-65 equipment set
 1. With internal accu and logger + charger
 2. RS485 with MODBUS
 3. Measures VX, VY, VZ and Vx, computes angles and velocity modulo, 1 sec or longer Δt
 4. With individual calibration chart
 5. Standard uncertainty 0.5%



- As **redundant measurement** Acoustic Doppler Velocitymeters ADVs used
 6. Two NORTEC VECTOR probes
 7. Horizontal installation types
 8. **Calibrated in working conditions**, compared to EM probes

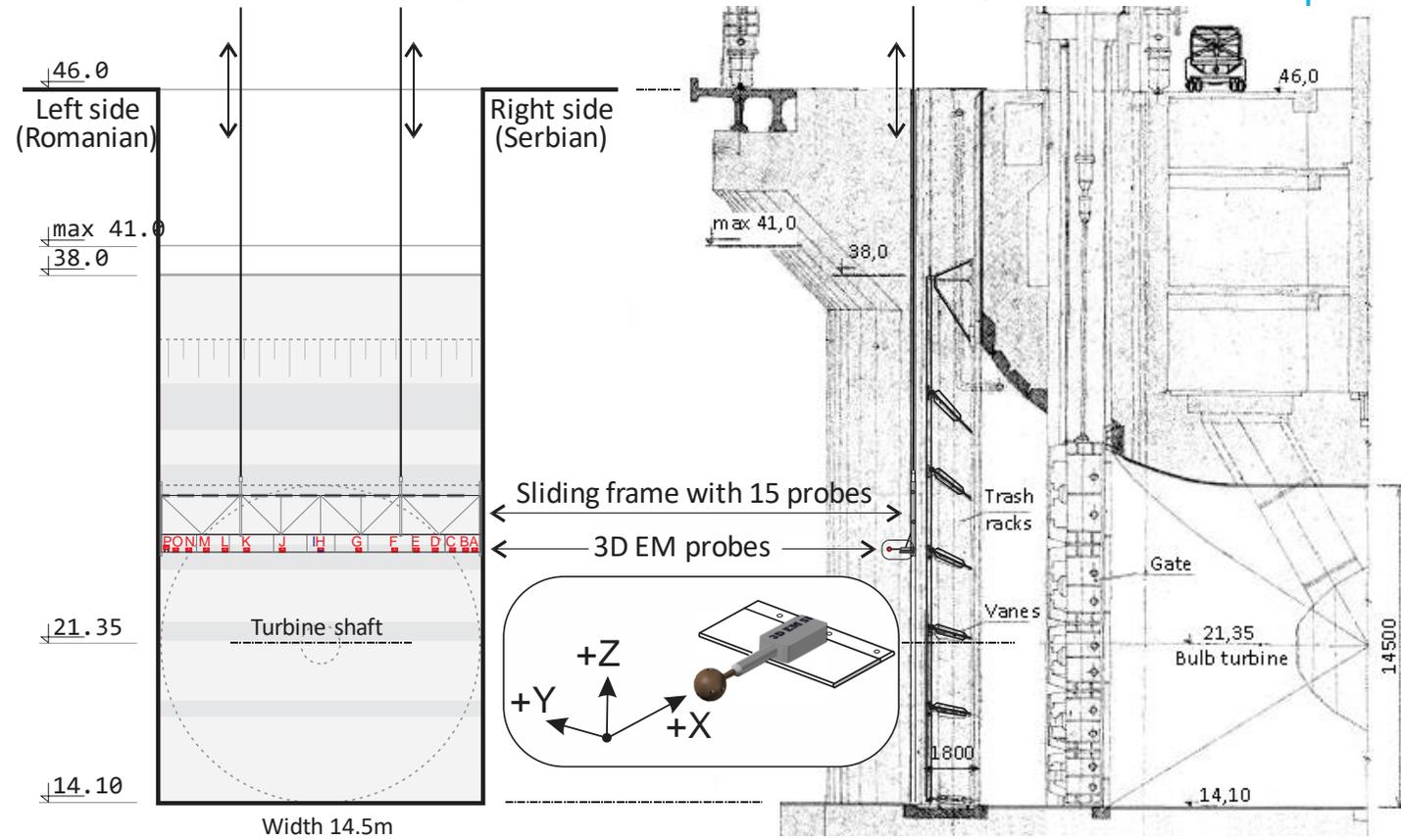
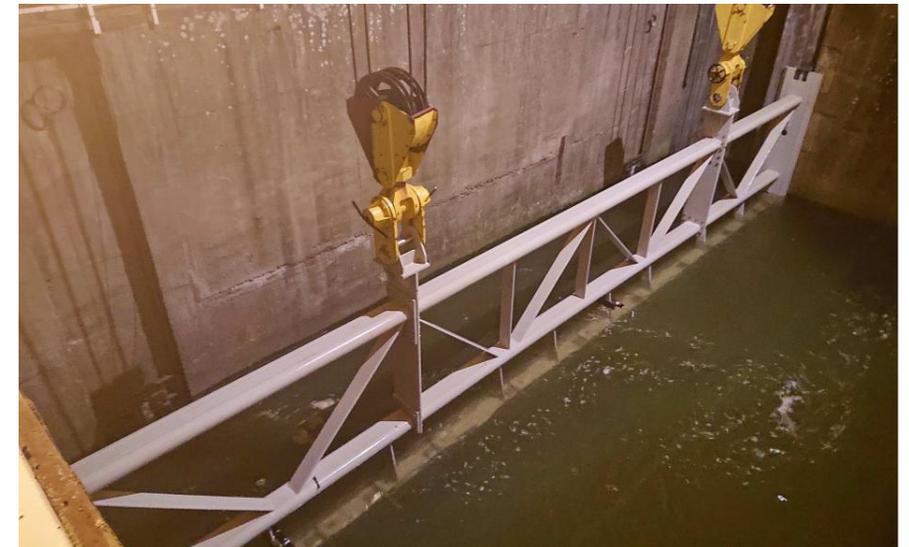




Back to the topic – measuring system

- System description:

1. Robust steel frame: $W = 14.5\text{ m}$, $H = 3.1\text{ m}$
Shaped to minimize flow disturbances
2. Installed **upstream of trash rack** in grapple niche



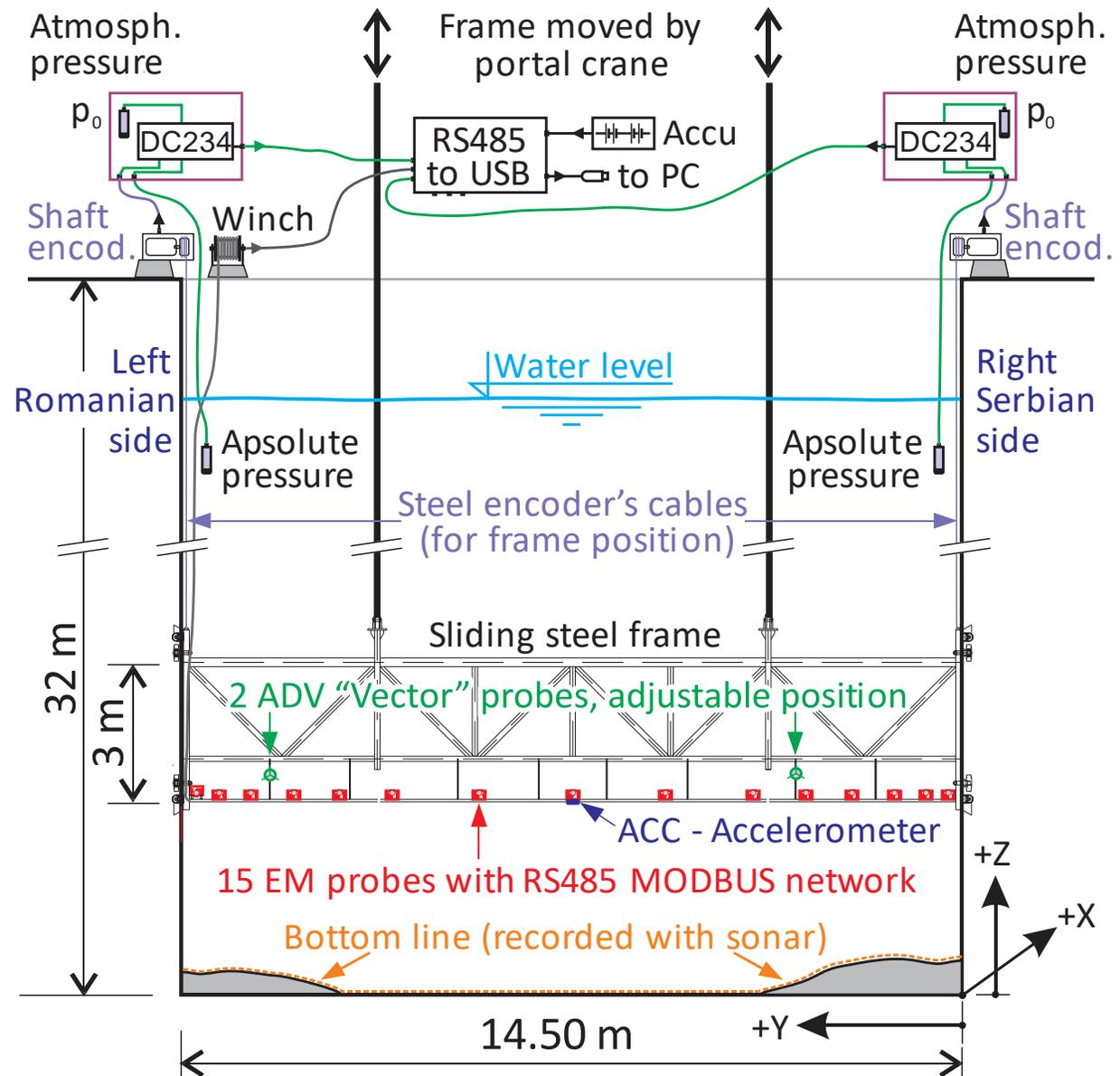


Measuring network



- System description:

- Robust steel frame: $W = 14.5 \text{ m}$, $H = 3.1 \text{ m}$
Shaped to minimize flow disturbances
- Installed upstream of trash rack in grapple niche
- RS485 network that connects to USB on PC:
 - 15 - 3D+EM probes
 - 2 - Frame position transducers
 - 2 - Pressure/level transducers
- 2 - Acoustic Doppler Velocity meters (ADV)
- 4 - Ultrasound sonars for bottom profile
- Turbine data off-line from SCADA



Measuring network and software

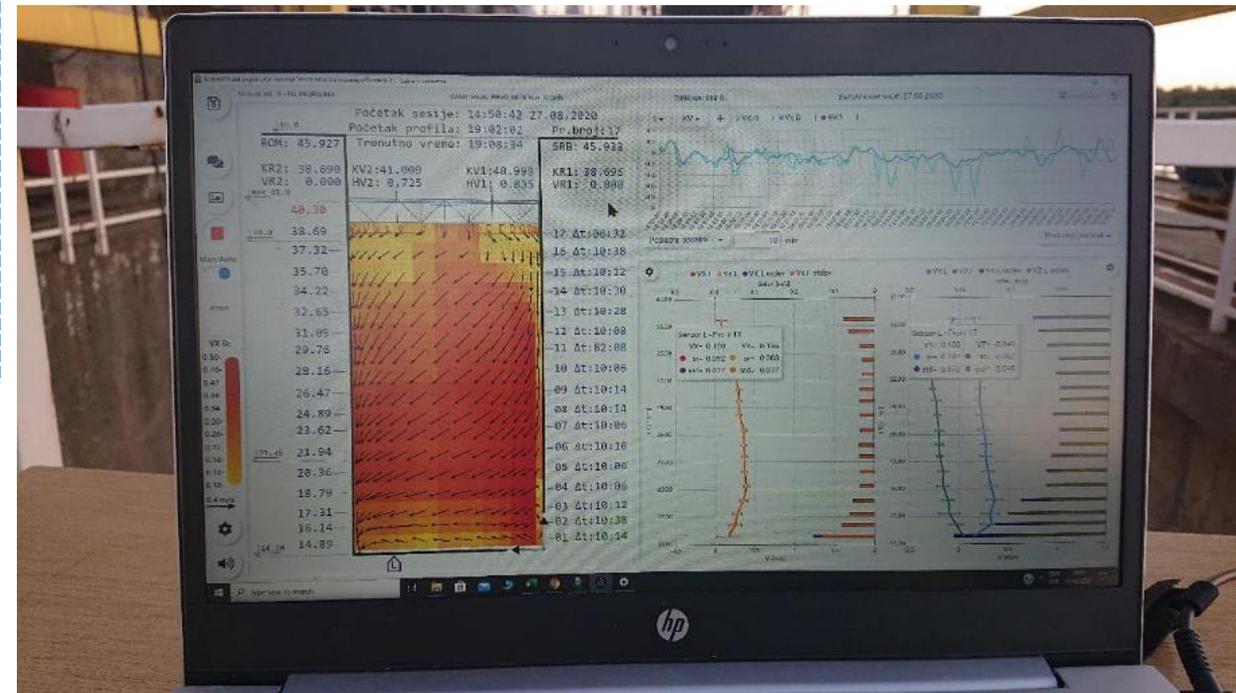
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15 - 3D+EM probes
2 - Frame position transducers
2 - Pressure/level transducers
4. 2 - Acoustic Doppler Velocitymeters (ADV)
5. 4 – Ultrasound sonars for bottom profile
6. Turbine data off-line from SCADA
7. **Real time data preview on PC with acquisition**

Once powered, the system is continuously sampling data with $\Delta t=2$ sec...

- Additional considerations

- During the measurements, the flow conditions at the analyzed and neighboring turbines should be kept “constant”
- Measurements were synchronized with HPP’s SCADA





Two operating modes

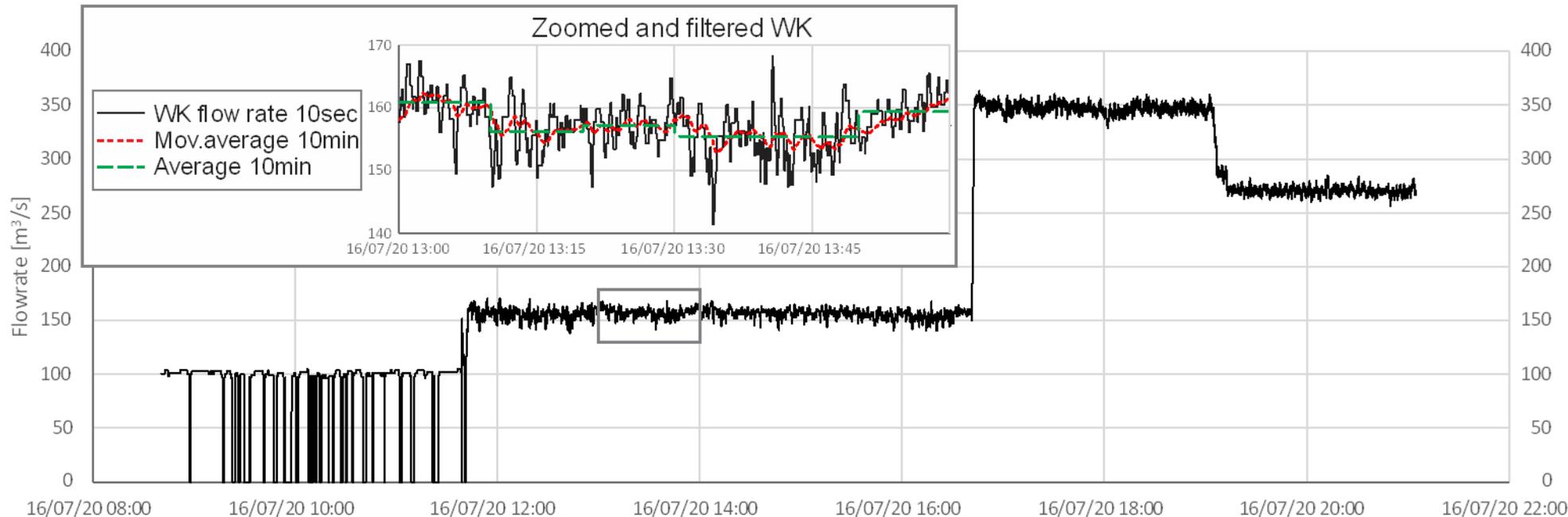


- **Incremental mode (primary mode)**

1. Steel frame is incrementally traversed between equidistant (~1.0 to 1.5 m) profiles
2. About 18 profiles
3. Measurement time ~ 3 hours (**for 10 min per profile**)

- **Continuous mode (tested)**

4. Steel frame is continuously traversed from bottom to the top
5. Constant traversing speed ~ 0.05 m/s (average water depth ~ 26.0 m)
6. Measurement time up to 9 minutes





Two operating modes



- **Incremental mode (primary mode)**

1. Steel frame is incrementally traversed between equidistant (~1.0 to 1.5 m) profiles
2. About 18 profiles
3. Measurement time ~ 3 hours (for 10 min per profile)

Comment:

- Accuracy good
- Too slow procedure
- Hard to keep (semi)constant operating conditions

- **Continuous mode (tested)**

4. Steel frame is continuously traversed from bottom to the top
5. Constant traversing speed ~ 0.05 cm/s (average water depth ~ 26.0 m)
6. Measurement time up to 9 minutes

Comment:

- Too fast frame's speed
- Data acquisition rate should be higher
- To achieve needed accuracy, several repetitions are needed

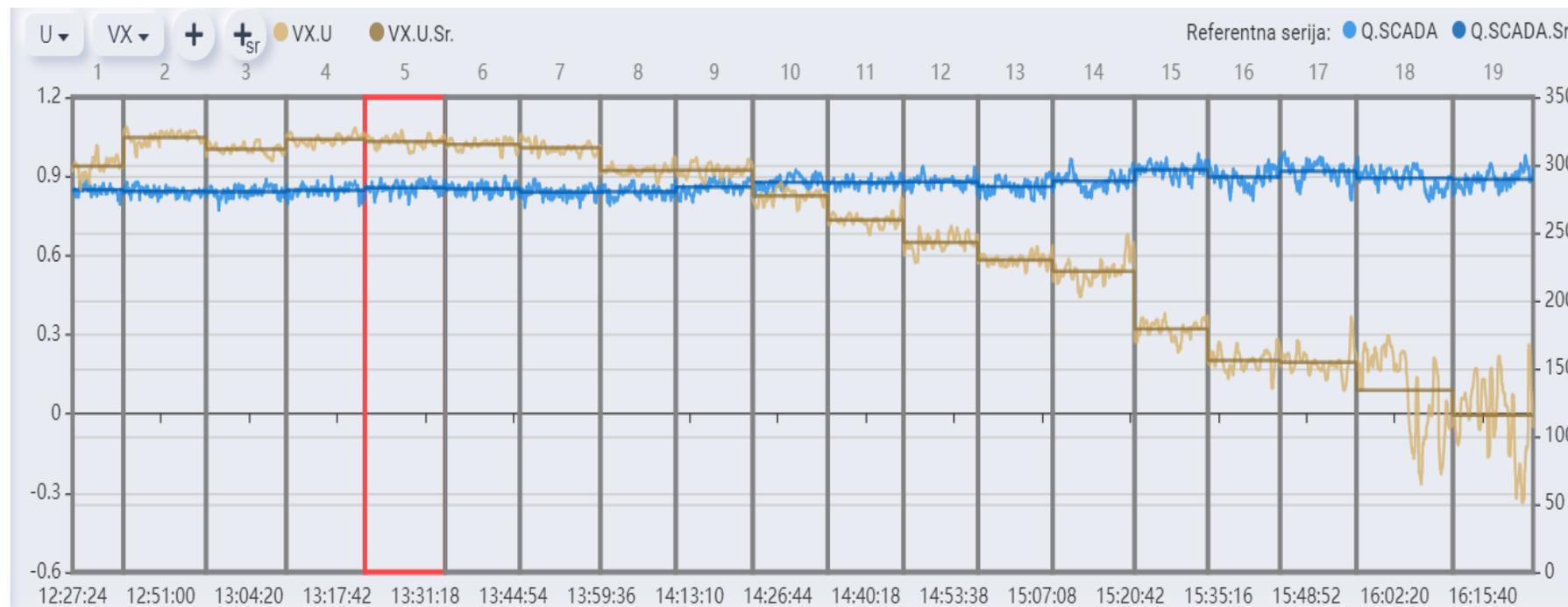


Off-line data postprocessing



- Post-processing software

1. Custom made
2. Data from ADVs downloaded and imported
3. Turbine data downloaded from SCADA
4. Visual check
5. **Select referent period**



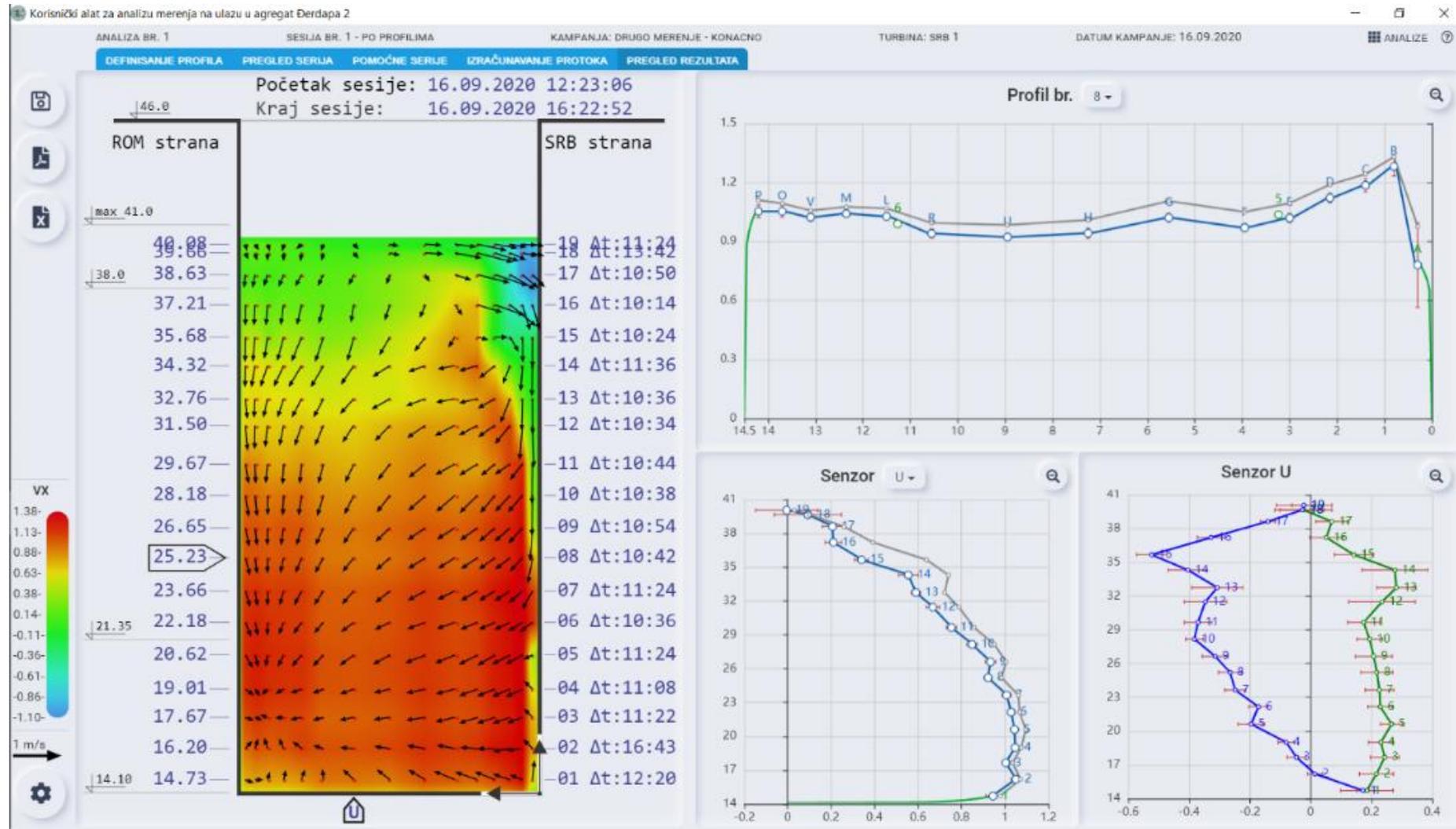


Off-line data postprocessing



- Post-processing software

1. Custom made
2. Data from ADVs downloaded and imported
3. Turbine data downloaded from SCADA
4. Visual check
5. Select referent period
- 6. Manual correction of selected probe**
7. Select extrapolation type





Off-line data postprocessing



- Post-processing software

- | | |
|---|--|
| 1. Custom made | 8. Calculate flowrate per sections |
| 2. Data from ADVs downloaded and imported | 9. See changes during corrections |
| 3. Turbine data downloaded from SCADA | 10. See the uncertainty components (details in following presentation) |
| 4. Visual check | |
| 5. Select referent period | |
| 6. Manual correction of selected probe | |
| 7. Select extrapolation type | |

Discharge measurement uncertainties:

- 1. Incremental mode: about 1 %
- 2. Continuous mode: up to 5 %

Total computed flowrate
Ukupan izračunati protok 295.188 m³/s

i Kombinovana mera nesigurnosti 1.08%
Combined uncertainty

Flow through left part Protok leve strane 7.021 m ³ /s (2.38%)	Flow through upper part Protok gornjeg dela -0.216 m ³ /s (-0.07%)	Flow through right part Protok desne strane 2.209 m ³ /s (0.75%)
	Flow through central part Protok centralnog dela 280.474 m ³ /s (95.02%)	
	Flow through lower part Protok donjeg dela 5.701 m ³ /s (1.93%)	

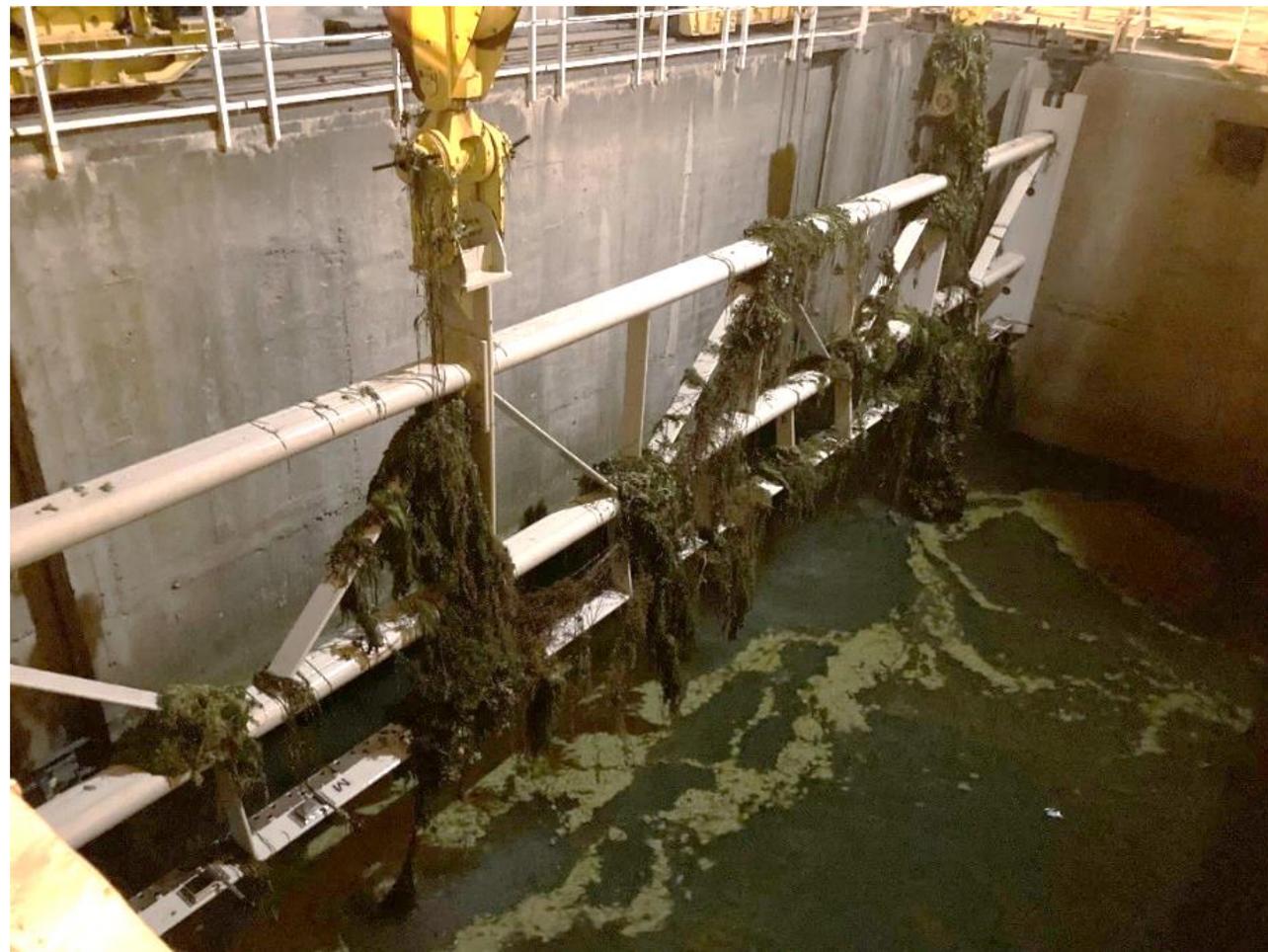


Measurement on two turbines (2020)



- In 2020, the measurement system was used on two turbines of the Iron Gate 2 HPP
 1. (Almost) Constant power on the analyzed and neighboring turbines
 2. Tested turbine in constant power mode (was this the best choice?)
 3. Water flow was carrying a significant amount of the **river vegetation**, trash and other debris

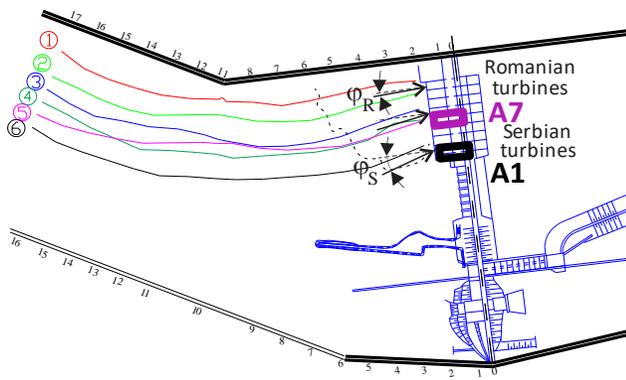
Even in those conditions the 3+D EMVMs and ADVs managed to capture good quality data



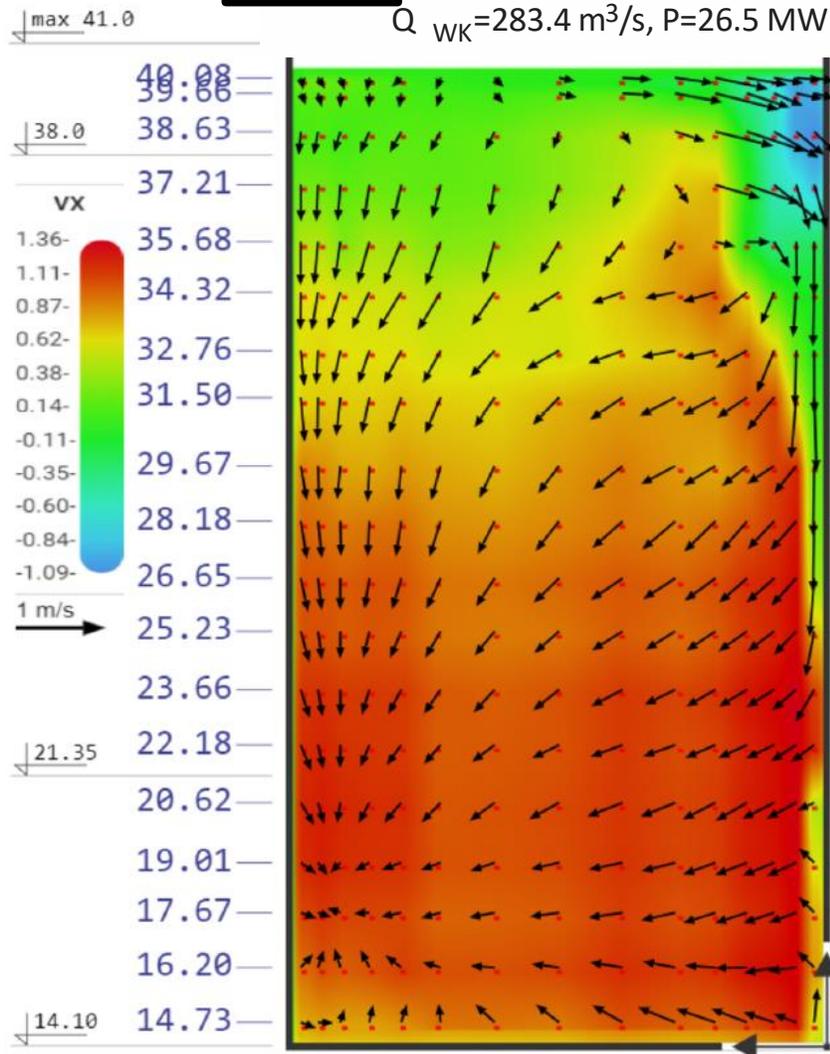
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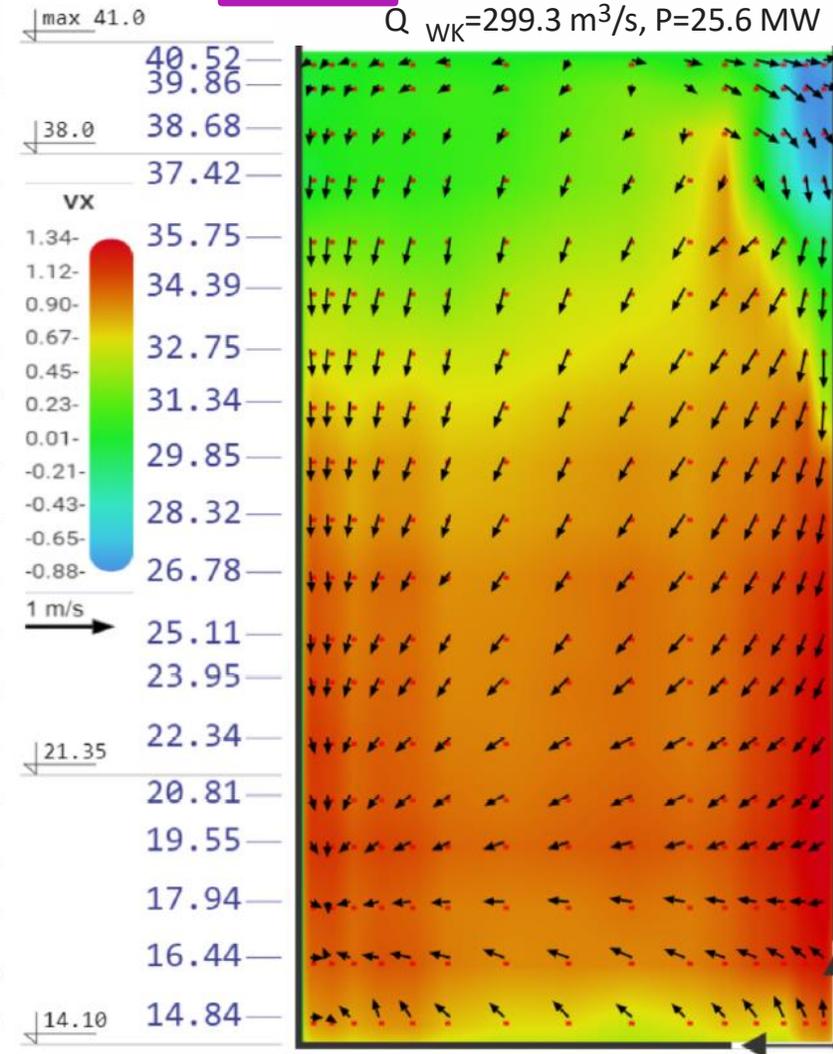
- (Almost) Constant power
- Tested turbine in constant this the best choice?)
- Water flow was carrying a of the river vegetation, tra debris
- Three flowrates:
 $Q_{min} (<100 \text{ m}^3/\text{s})$
 $Q_{mean} (180-200 \text{ m}^3/\text{s})$
 $Q_{max} (300 \text{ m}^3/\text{s})$



Turbine A1 $Q_{MEAS} = 295.2 \text{ m}^3/\text{s}$ (unc. 1.1%)
 $Q_{WK} = 283.4 \text{ m}^3/\text{s}$, $P = 26.5 \text{ MW}$



Turbine A7 $Q_{MEAS} = 288.6 \text{ m}^3/\text{s}$ (unc. 1.16%)
 $Q_{WK} = 299.3 \text{ m}^3/\text{s}$, $P = 25.6 \text{ MW}$





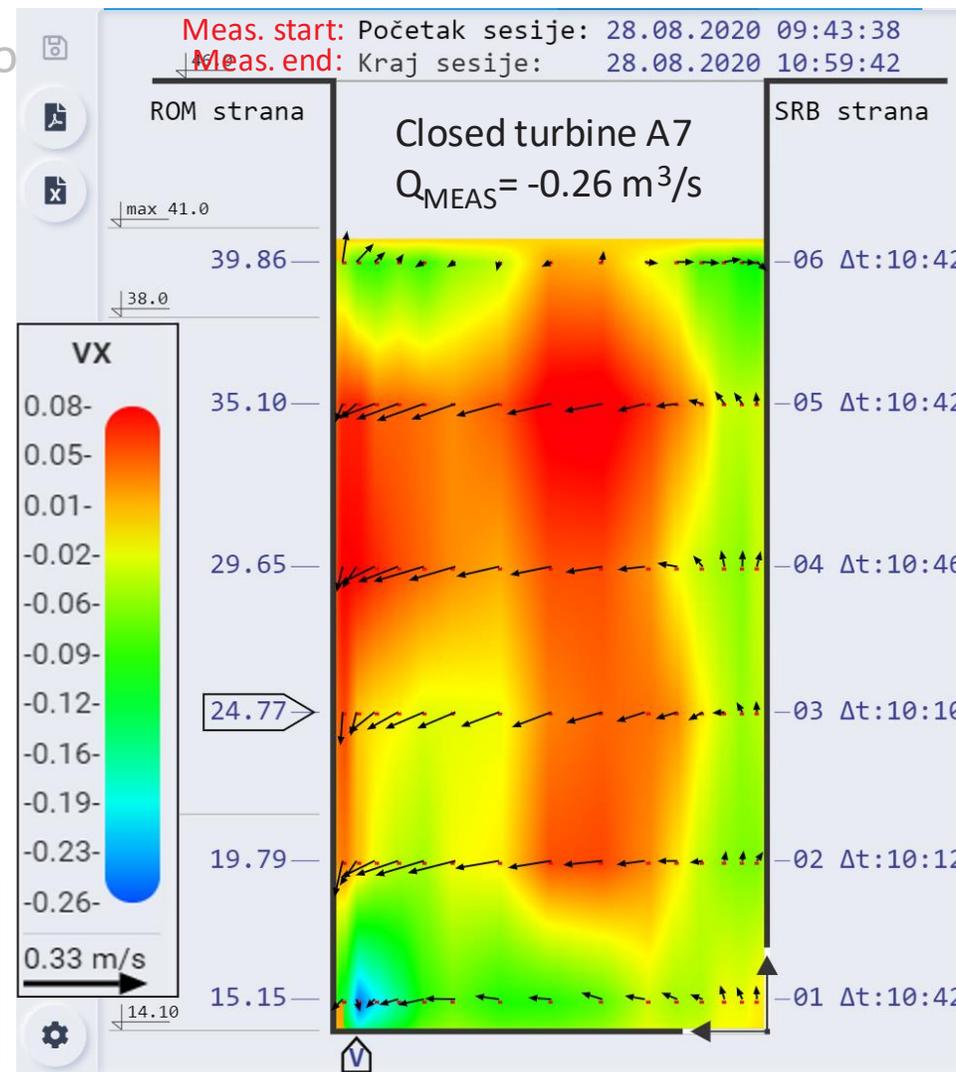
Measurement on two turbines (2020)



- In 2020, the measurement system was used on two turbines of the Iron Gate 2 HPP

- (Almost) Constant power on the analyzed and neighboring turbines
- Tested turbine in constant power mode (was this the best choice?)
- Water flow was carrying a significant amount of the river vegetation, trash and other debris
- Three flowrates:
 Q_{min} ($< 100 \text{ m}^3/\text{s}$)
 Q_{mean} ($180\text{-}200 \text{ m}^3/\text{s}$)
 Q_{max} ($300 \text{ m}^3/\text{s}$)
- Measurement on **closed turbine A7**, neighboring turbines on maximal power

Only six horizontal profiles were used.
Calculated flow $-0.26 \text{ m}^3/\text{s}$
($< 0.1 \%$ of nominal flow rate)



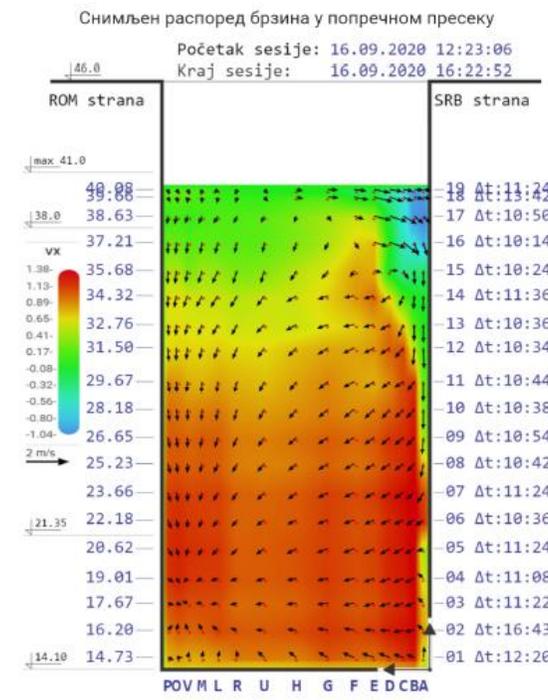


Measurement on two tu

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 - (Almost) Constant power on the analyzed and neighboring turbines
 - Tested turbine in constant power mode (was this the best choice?)
 - Water flow was carrying a significant amount of the river vegetation, trash and other debris
 - Three flowrates:
 - Qmin (<100 m³/s)
 - Qmean (180-200 m³/s)
 - Qmax (300 m³/s)
 - Measurement on closed turbine, neighboring turbines on maximal power
 - For each measurement, **printed report produced**

Записник са снимања поља брзина и обрачуна протока на турбини ХЕ Ђердап 2

Датум обављеног мерења: 16.09.2020 у времену од: 12:23:06 до: 16:22:52.
 Референтни профил број: 5 у времену од: 13:22:44 до: 13:34:08.
 Турбина А1 са активном снагом на генератору у референтном периоду од 26.50 MW, средњим протоком у референтном периоду Q_WK 283.35 m³/s, и нето падом у референтном периоду од 9.51 m.



Обрачунат проток по мерним зонама

Укупан израчунати проток 295.188 m³/s
Комбинована мерна несигурност 1.1%

Проток леве стране 7.021 m ³ /s (2.38%)	Проток горњег дела -0.216 m ³ /s (-0.07%)	Проток десне стране 2.209 m ³ /s (0.75%)
	Проток централог дела 280.474 m ³ /s (95.02%)	
	Проток доњег дела 5.701 m ³ /s (1.93%)	

Део	Метода екстраполације	Образац
Површина:	Линеарна	$V_x = 0.53 * Z^{-21.26}$
Румунија:	Експоненцијална	$V_x = 0.94 * Z^{1/9}$
Србија:	Експоненцијална	$V_x = 0.29 * Z^{1/9}$
Дно:	Експоненцијална	$V_x = 0.92 * Z^{1/6}$



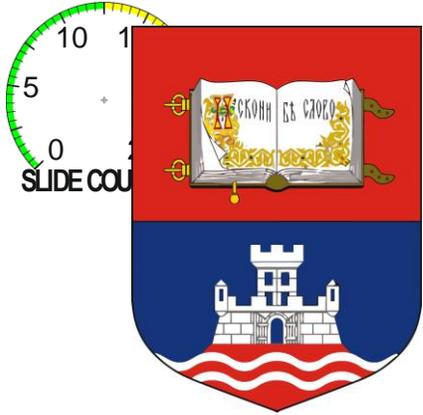
Conclusions



- Discharge measurement system was designed and applied at the intakes of the tubular turbines of the Iron Gate 2 HPP
- Short and converging intake along with the high incident flow angles inspired application of the new solutions
- Velocity-Area approach was adopted
- Steel frame with 15 novel 3D EMVMs was traversed for velocity field mapping
- Novel discharge measurement uncertainty assessment procedure yielded values just above 1 %.



Sunset from Iron Gate 2 HPP by Damjan Ivetić



University of Belgrade, Faculty of Civil Engineering



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IGHEM2022, Grenoble, France, 03-05 October, 2022



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