The VIVACE Converter

Enhancing Flow Induced Motions to Harness Hydrokinetic Energy in an Environmentally Compatible Way

Michael M Bernitsas, Ph.D.

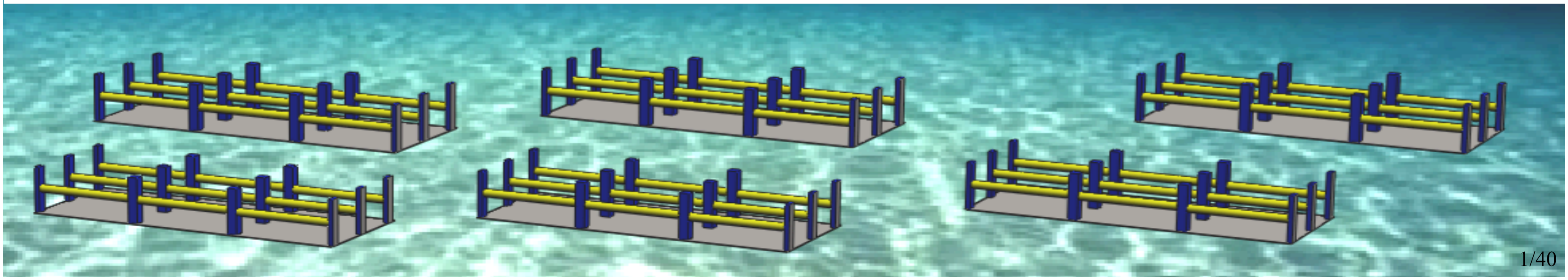
Mortimer E. Cooley Professor of NA&ME and ME

Director Marine Renewable Energy Laboratory

Marine and Hydrokinetic Device Modeling Workshop

National Wind Technology Center, Boulder CO

March 1, 2011



Outline

I. Concept

Enhancement of flow induced motions:
VIV, galloping, buffeting

II. Development of VIVACE

Stage 1: Channel – scale 2	Scales
Stage 2: Towing tank – scale 3	Stage 3: Open-water - scale 3

III. Research Advances

Virtual m-c-k	Turbulence stimulation
Galloping vs. VIV	Flow transition
PTC to FIM map	Multiple cylinders
CFD	Fish-tail

I.1. Concept: Enhance flow induced motions

VIV (Vortex Induced Vibration)

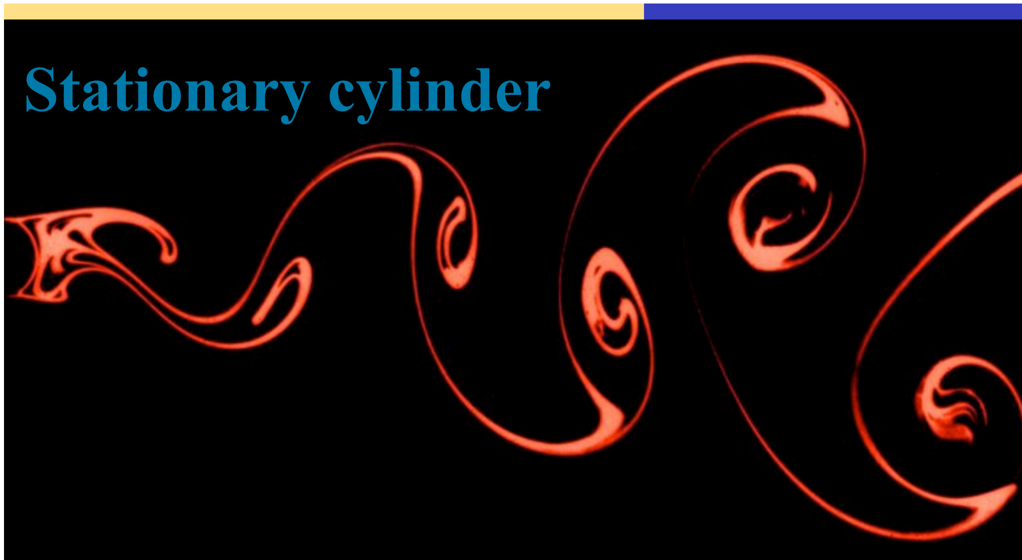
Galloping

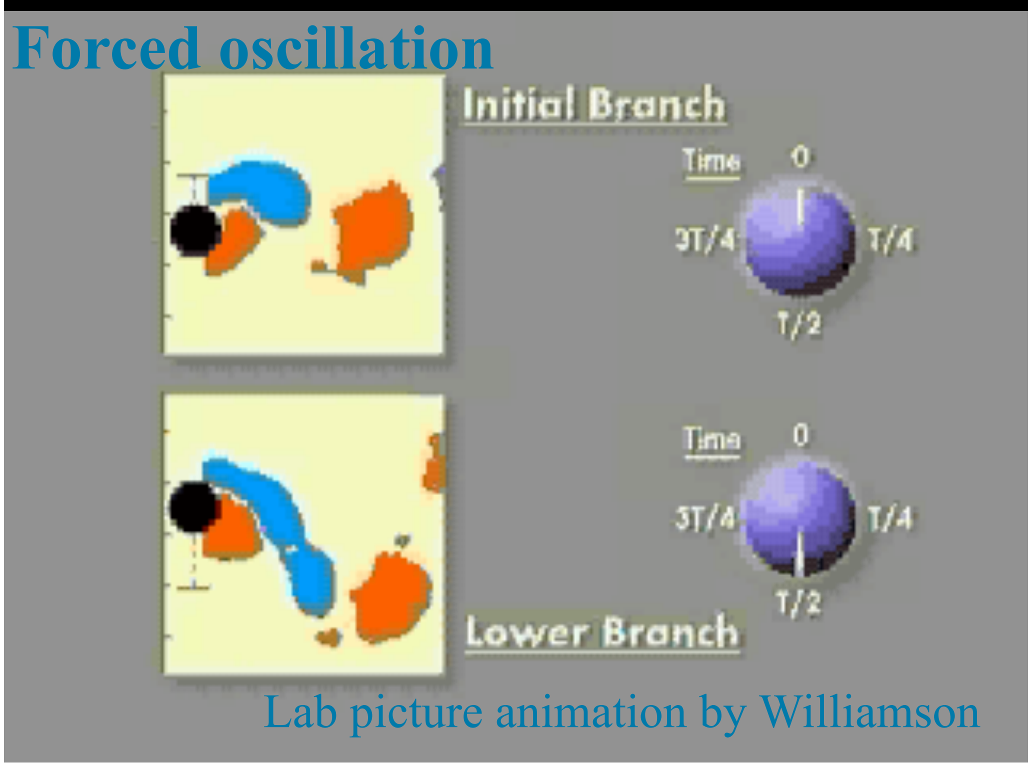
- Soft
- Hard
- Wake galloping
- Proximity galloping
- Interference galloping

Flutter

Buffeting

I.2. VIV





Lab picture animation by Williamson

Vortex Induced Vibration

- Elastic cylindrical body
- Rigid cylinder on elastic support

Features

- Vortex synchronization
- Synchronization lock-in

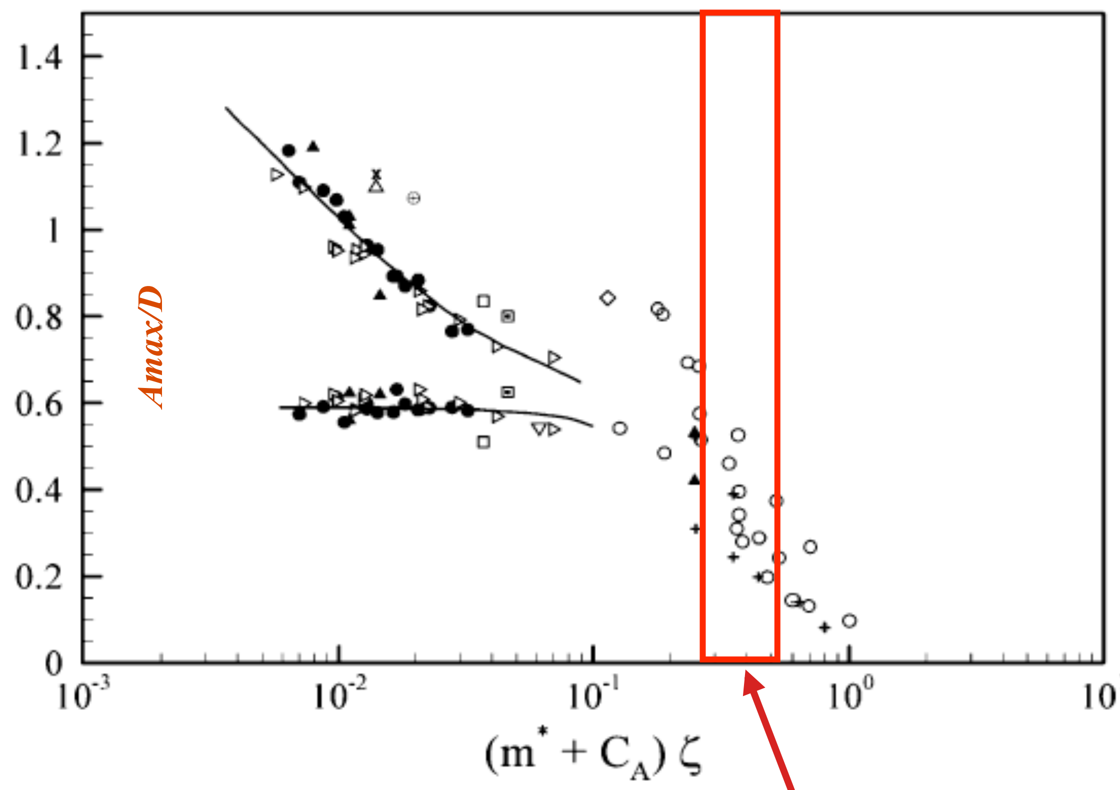
  at f_n +/- 50%-60%
- Self - limiting amplitude

  (forced oscillations)
- Initial, upper, and lower synchronization branches
- Vortex structures
- Hysteresis
- Correlation length

I.3. High damping VIV at $8\times10^3<Re<1.5\times10^5$

Smooth cylinder results → * A/D=1.9

Skop-Griffin Plot



Typical VIV tests are:

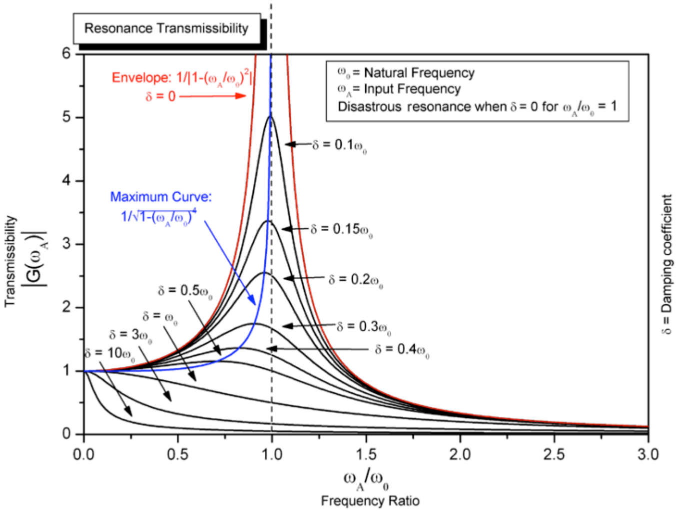
- Lab based with low Re and low damping
- Field based with high Re trying to suppress VIV

Few of these results are relevant to energy harness through VIV

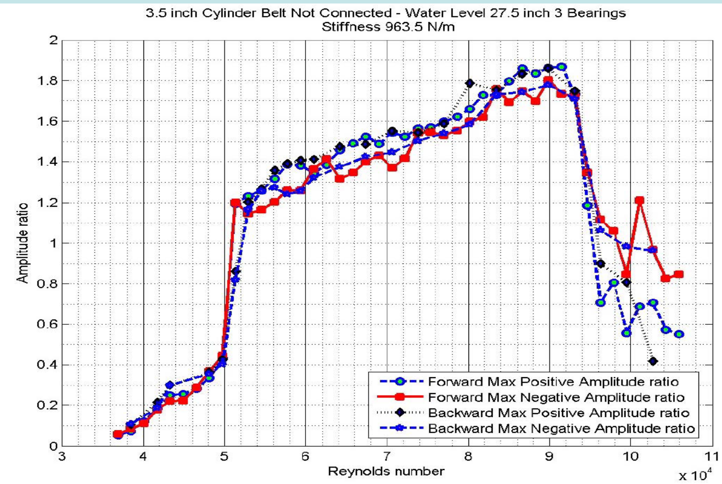
VIVACE tests

I.4. **Oscillators:** Linear and nonlinear

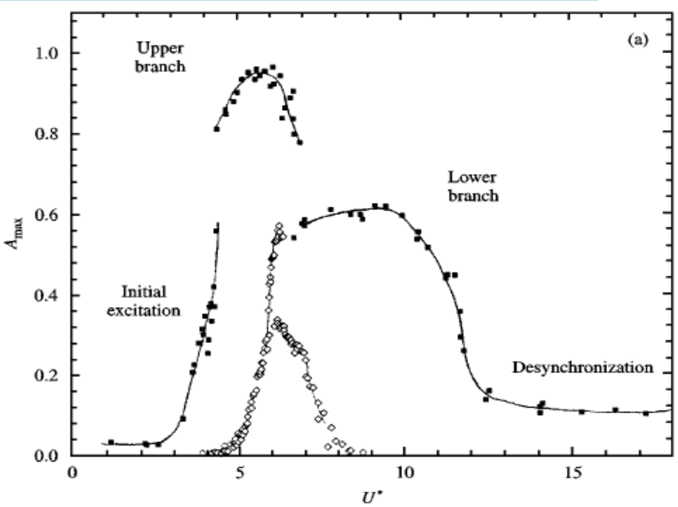
Linear oscillator



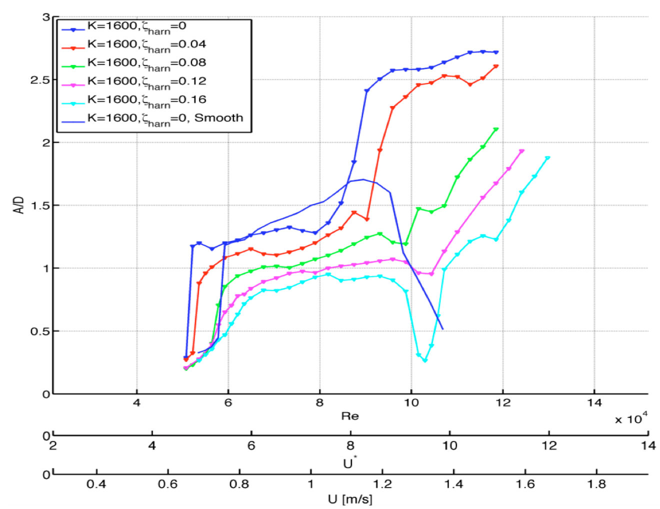
VIVACE, VIV high-Re oscillator



VIV, low-Re oscillator

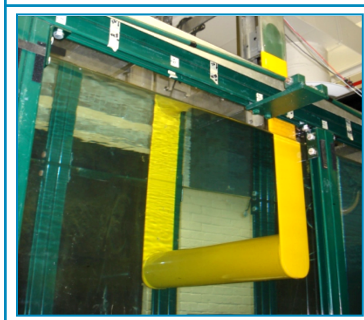
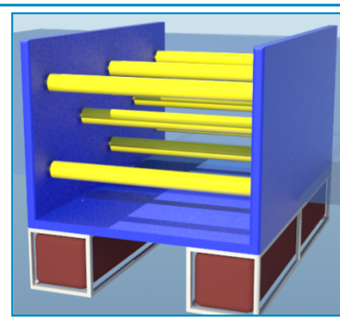
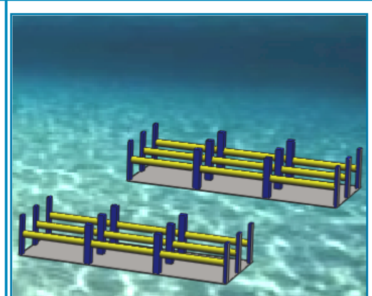
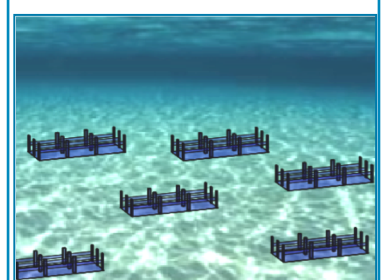


VIVACE, VIV+galloping oscillator



II.1. Development of VIVACE

- Stage 1: The concept
- Scales
- Stage 2: Proof of concept, channel tests
- Stage 3: Field tests

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Tidal-current energy conversion concept	Subsystem testing at intermediate scale	Subsystem testing at large scale	Full scale prototype testing	Commercial demonstrator testing
U of Michigan	U of Michigan	St. Clair River	St. Clair River	TBD
2005 to 2009	2009 to Present	Summer 2010	Summer 2011	Summer 2011
				

II.2. **Stage 1**: The concept

1940: Tacoma Narrows bridge collapsed due to wind-induced vibrations

1965: Ferrybridge cooling towers collapsed due to VIV

FIM can be controlled to generate energy!

II.3. How VIVACE works

Objective: Capture the abundant hydro-kinetic energy in even low-speed ocean/river currents without using dams or turbines

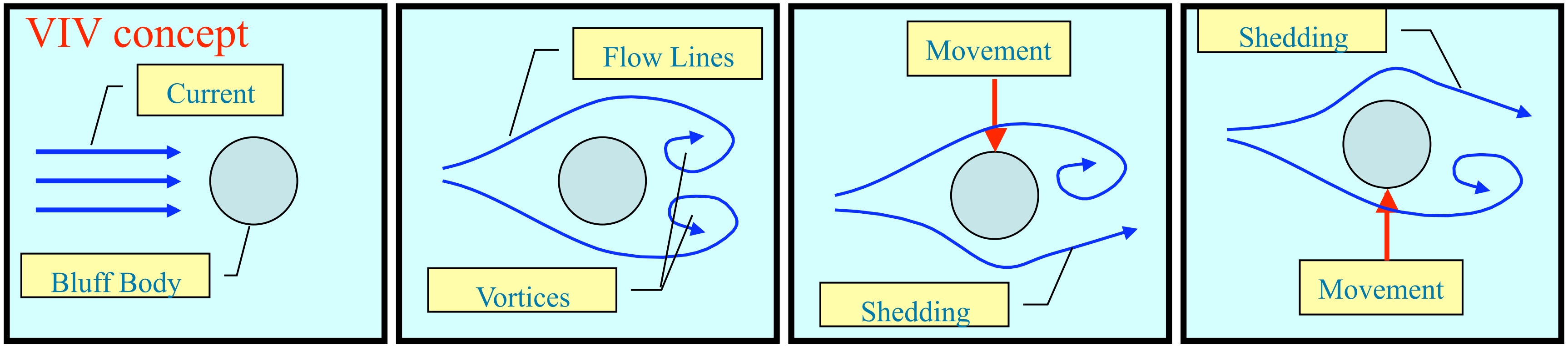
Approach: Develop technology that mimics and enhances natural phenomena: VIV, galloping

VIV: **Enhance** vortex shedding, **Harness** VIV energy

Galloping: **Enhance** instability, **Harness** VIV energy

Fish biomimetics: Surface **roughness**; cylinder **proximity**; passive **fish tail**

Concept: **FIM** converts hydrokinetic energy to transverse mechanical motion.

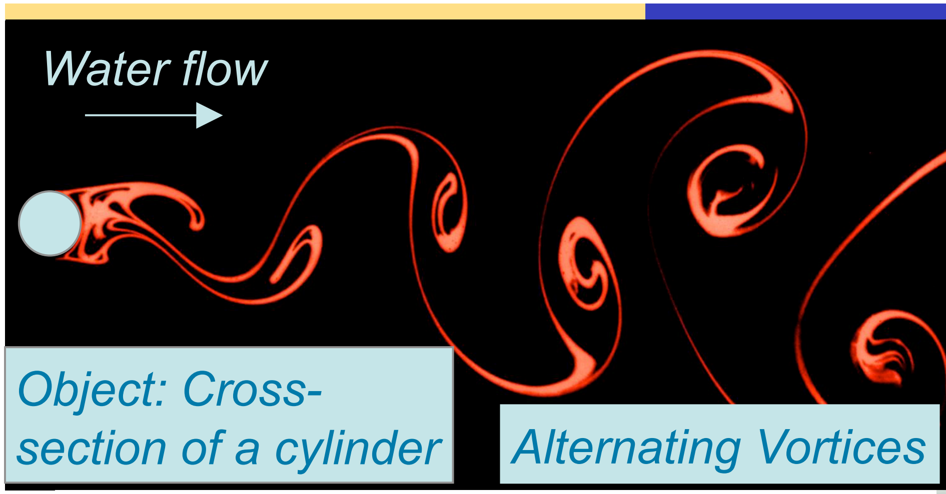


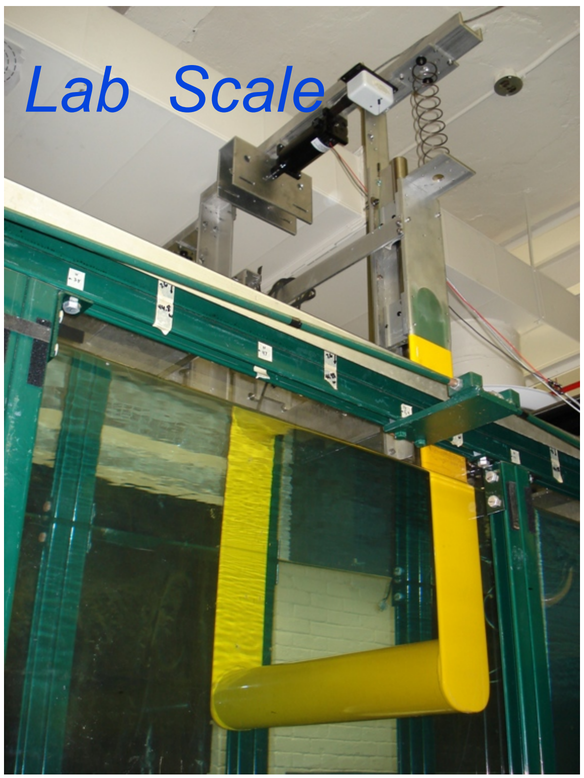
II.4. Stage 2: Proof of concept lab tests

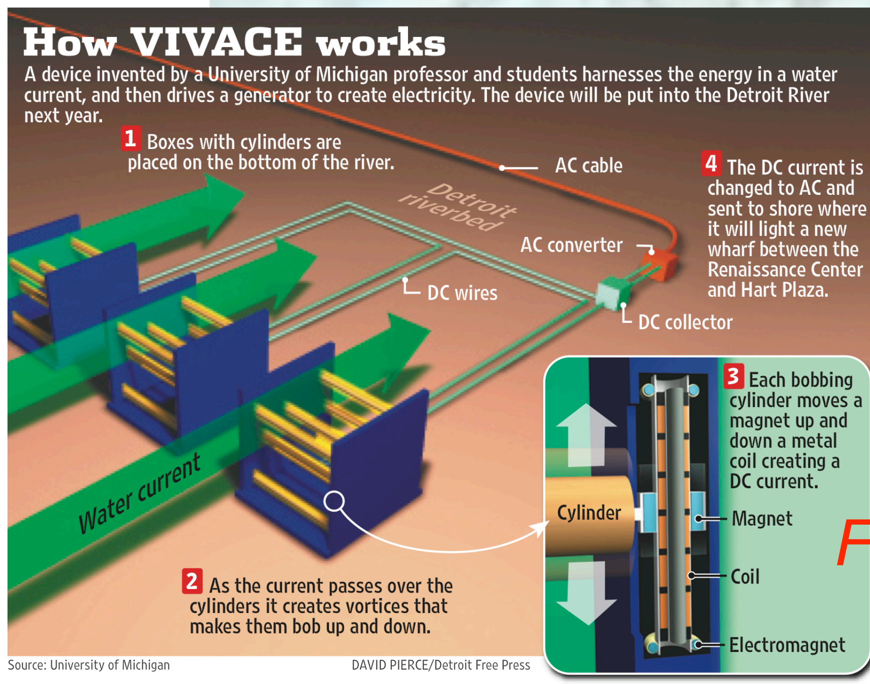
Flow Velocity U= 1.6knots (0.8m/s)

Synchronization
U=[0.56-1.05]m/s
at high damping,
K=2*518 N/m,
m*=1.45

II.5. VIVACE scalability & modularity

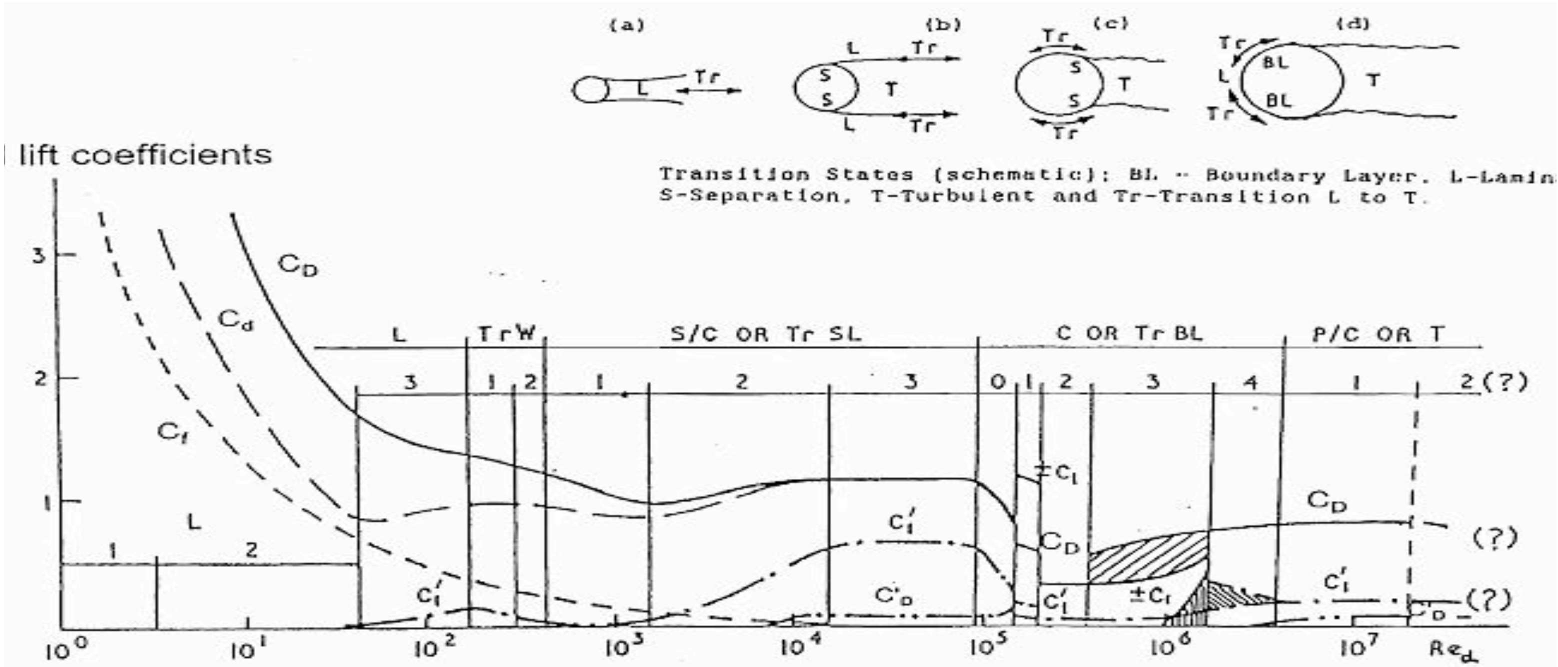






Farm Scale

VIVACE scales



Scale 1: P≤10W ⟺ 1,000≤Re≤20,000

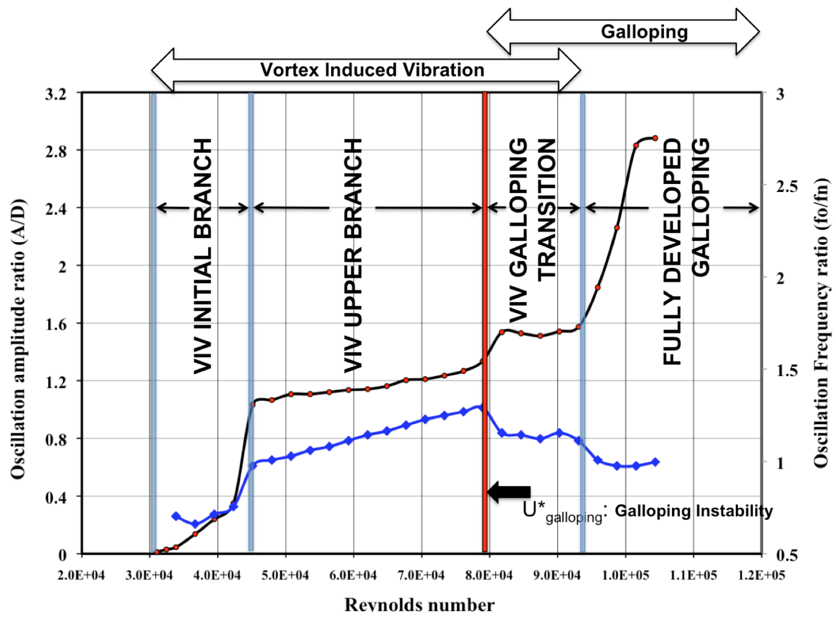
Scale 2: P≤200W ⟺ 20,000≤Re≤150,000

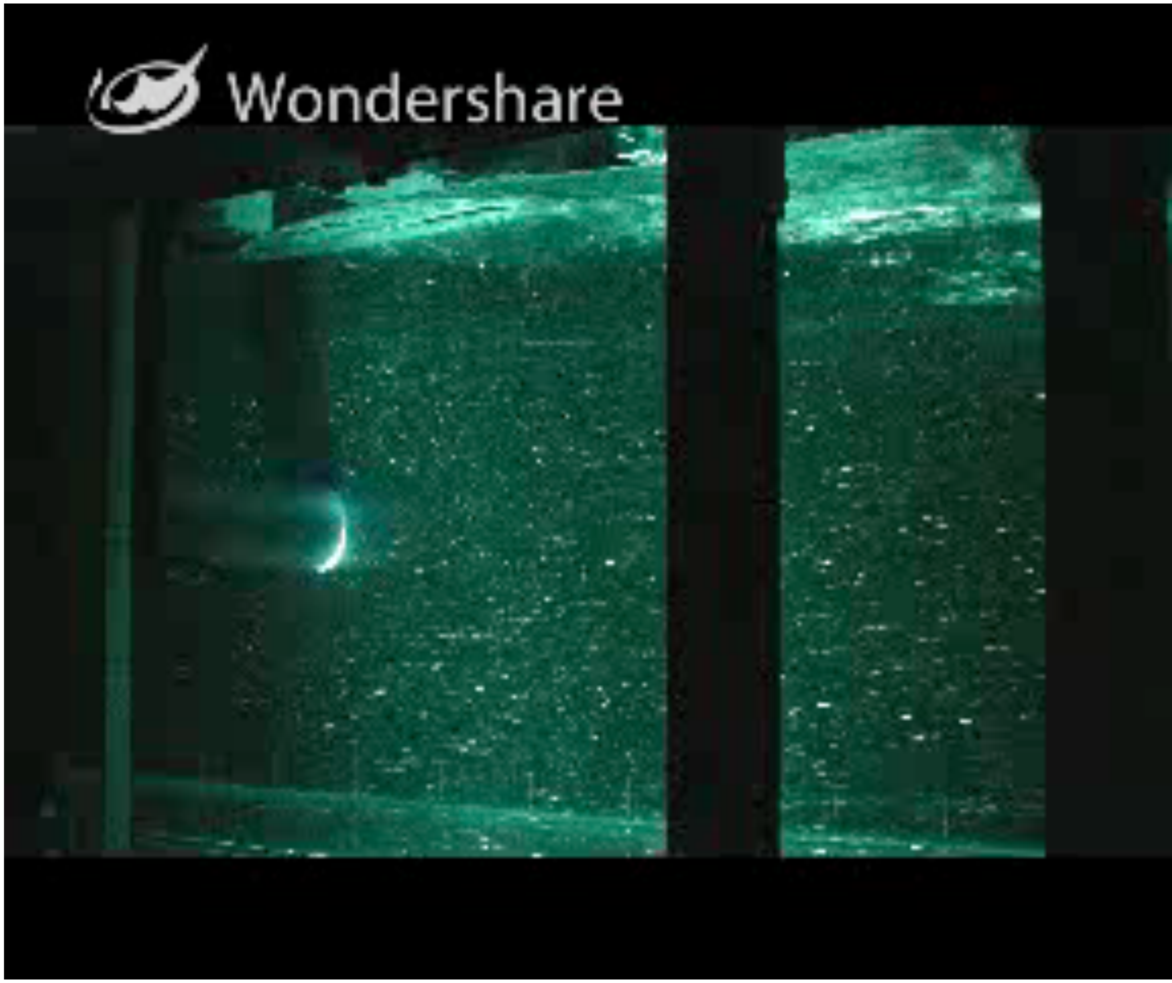
Scale 3: P≤5kw ⟺ 150,000≤Re≤500,000

Scale 4: P≤100kw ⟺ 500,000≤Re

4-cylinder VIVACE module

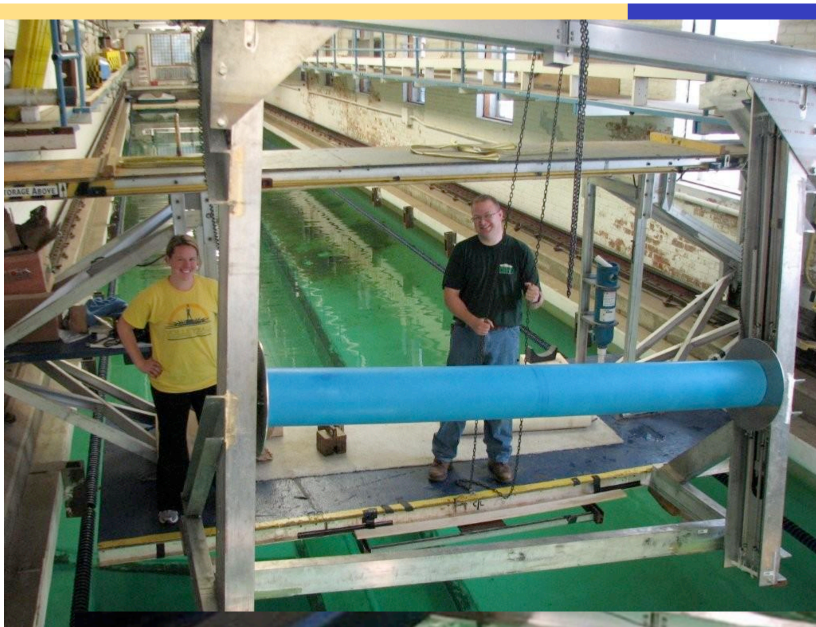
II.6. Enhance VIV & galloping

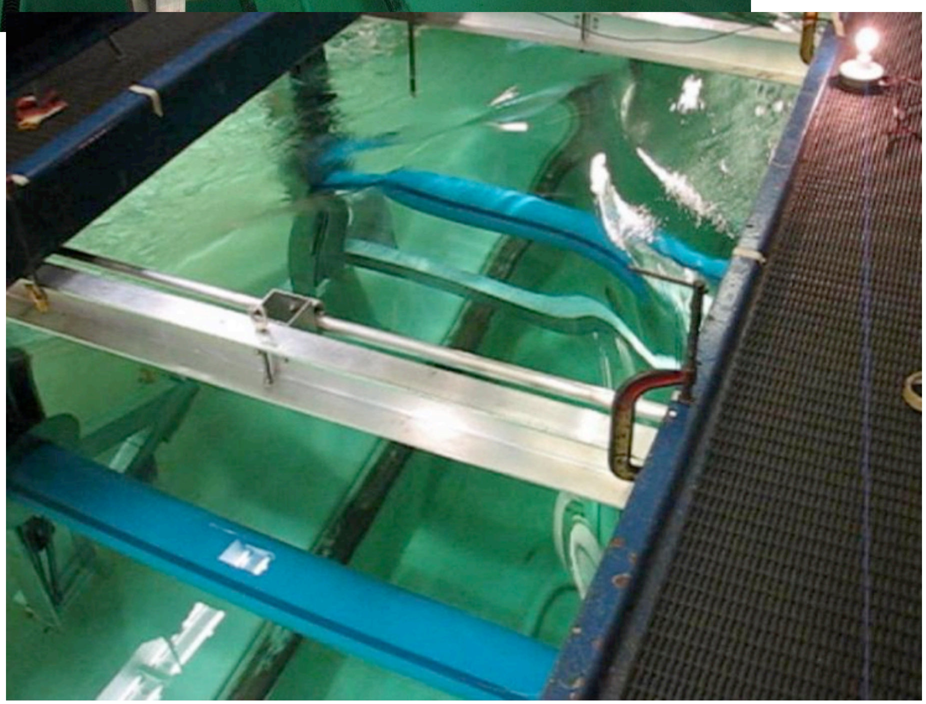




Fish biomimetics: Passive turbulence control A/D vs. U*

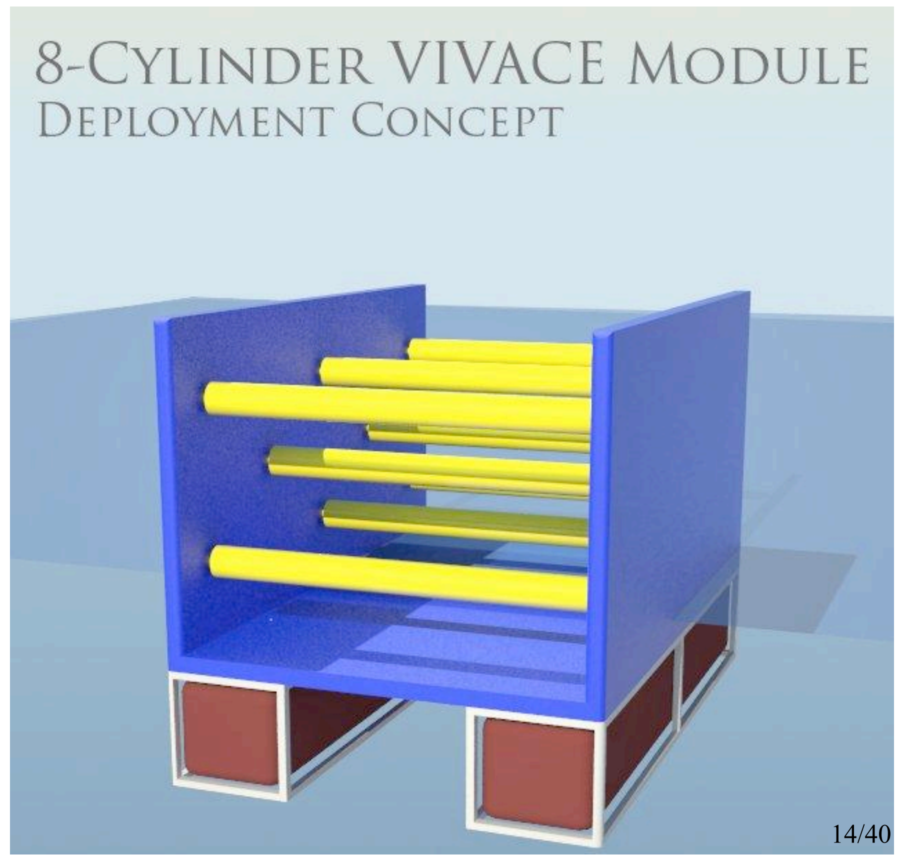
II.7. **Stage 3:** Prototype testing





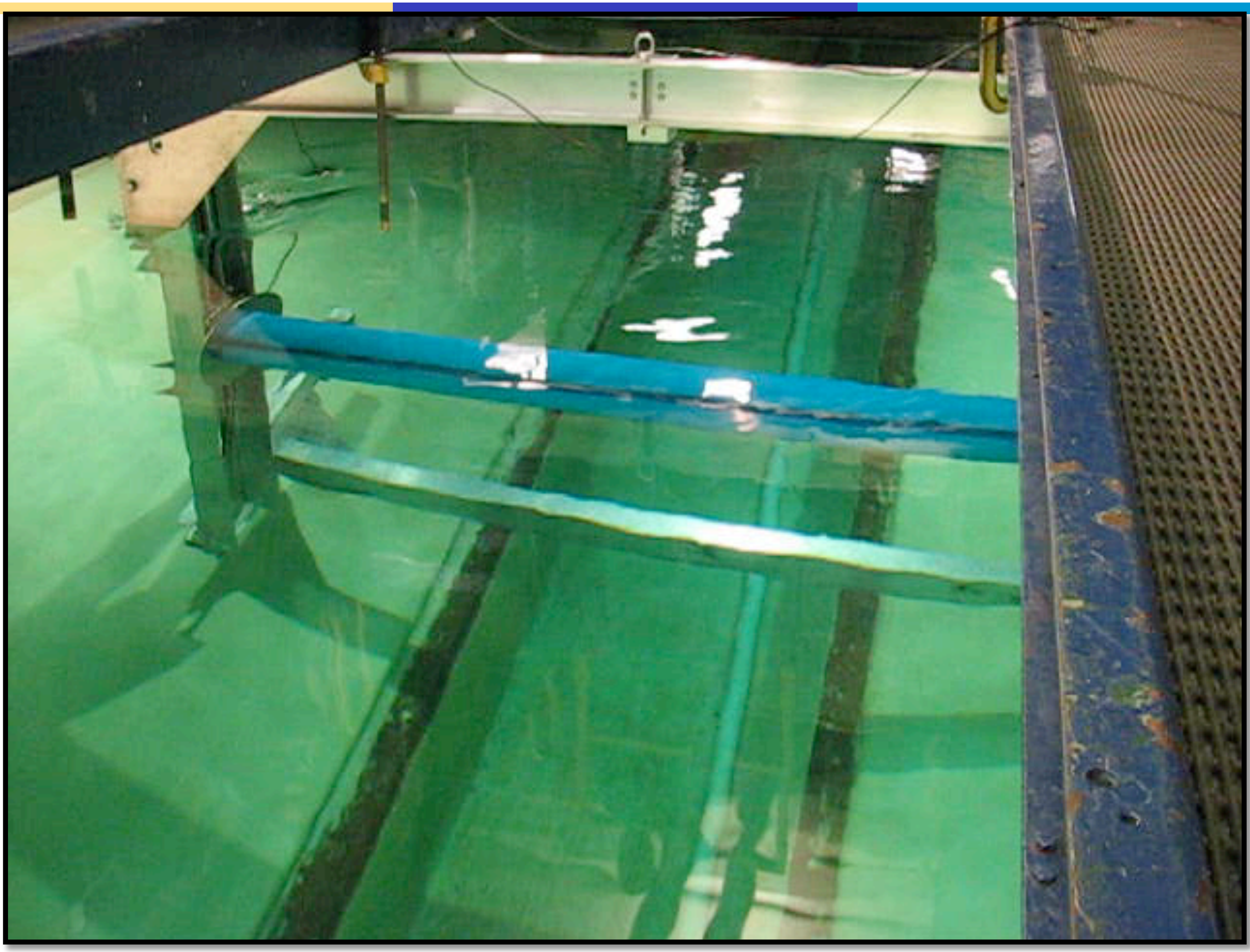
Univ. of Michigan towing tank:
Sept. 2009

St. Clair river: Summer 2010

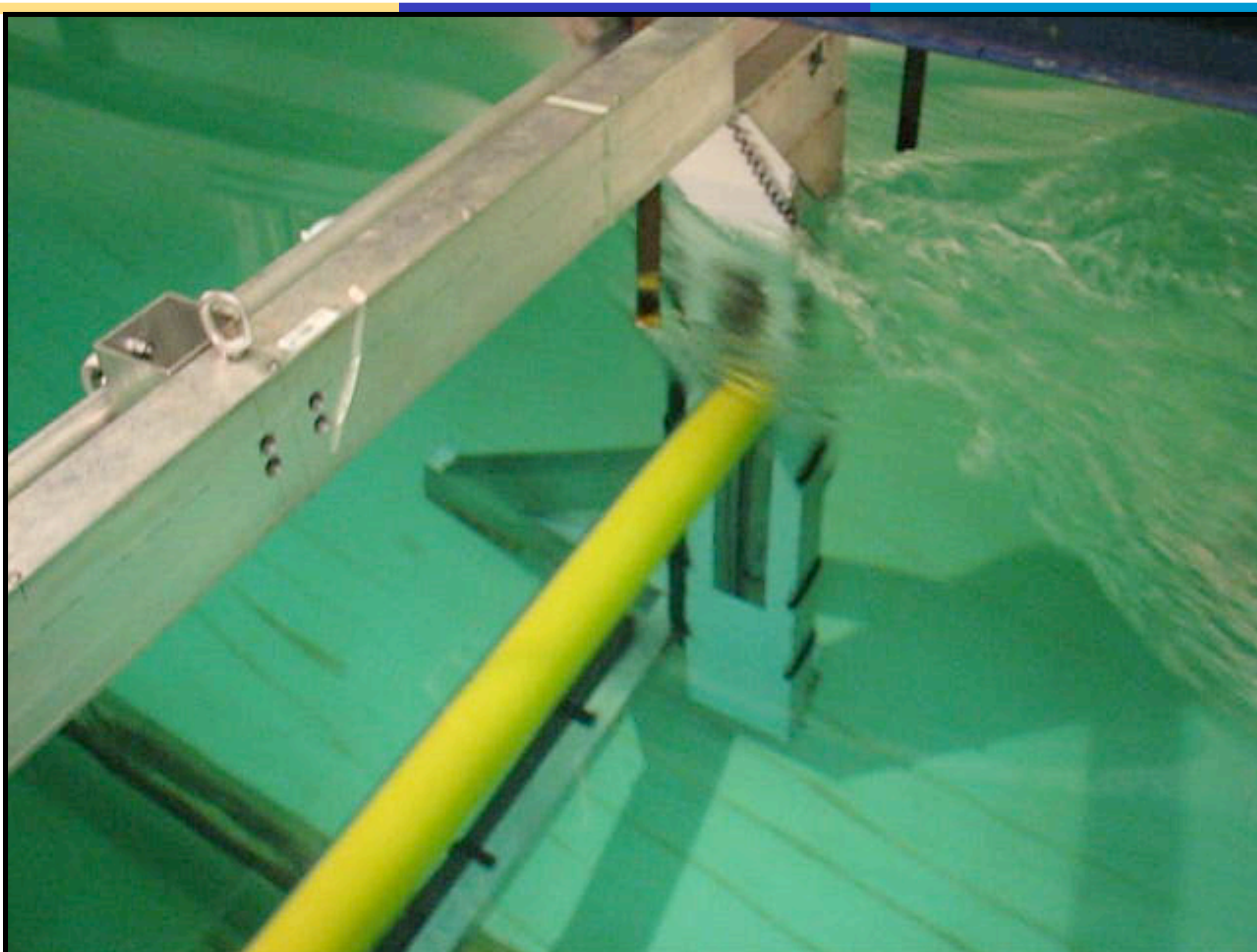


Lab tests: 1 cylinder, 1.9 knots

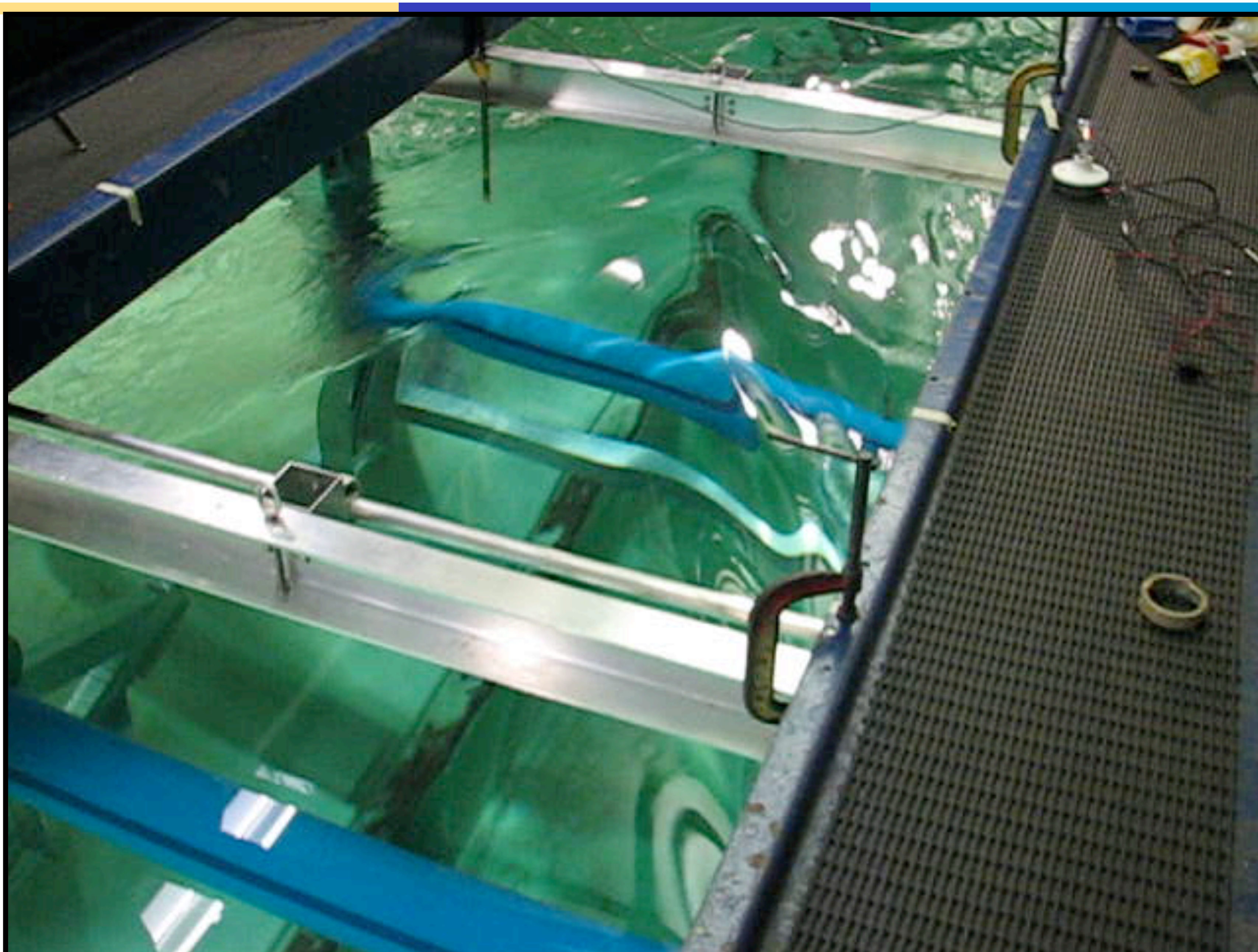
Lab tests: 1 cylinder with PTC, 2kn



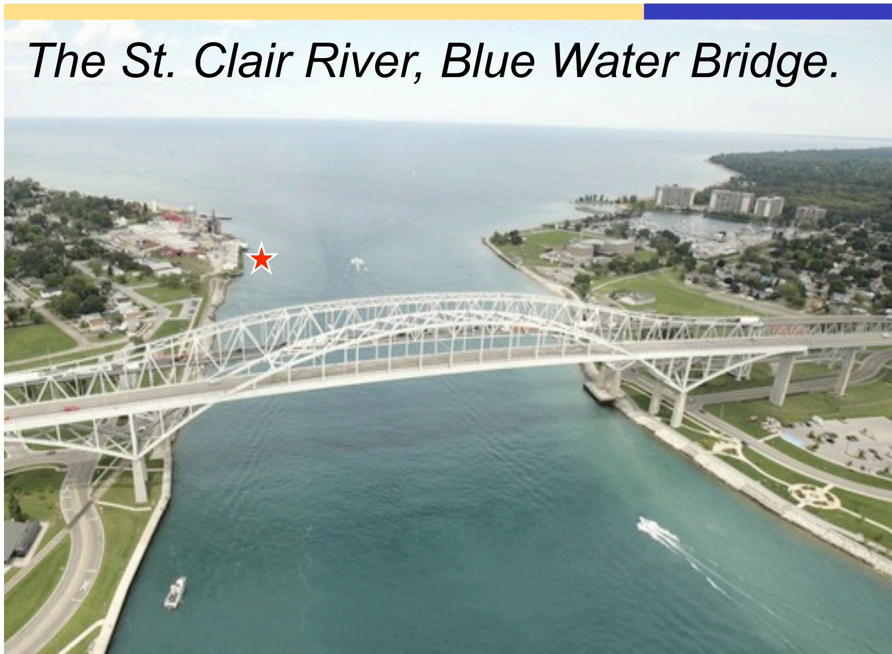
Lab tests: 1 cylinder with PTC, 2 knots



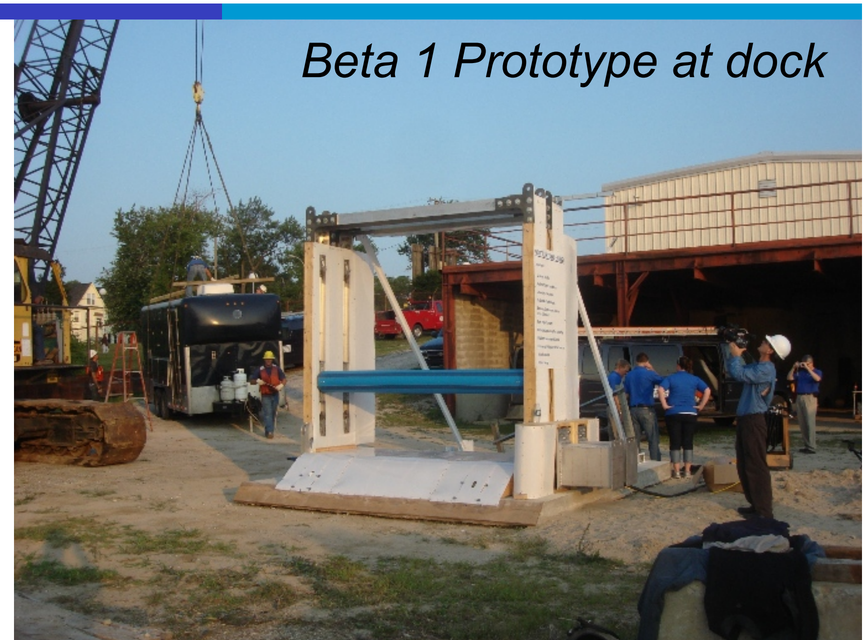
Lab tests: 2 cylinders with PTC, 2 kn



II.8. River deployment: 2 cylinders with PTC



The St. Clair River, Blue Water Bridge.



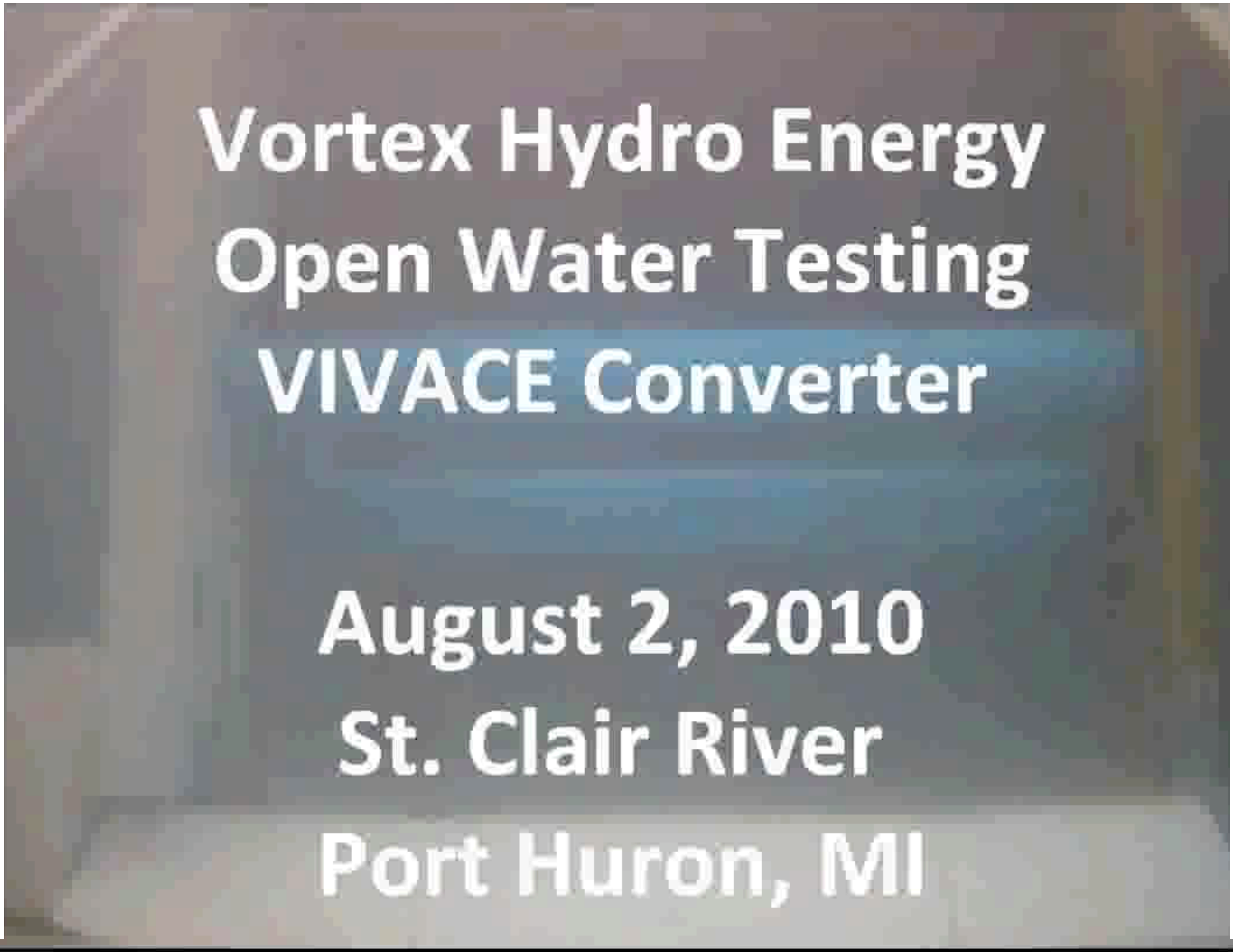
Beta 1 Prototype at dock

Beta 1 being tested in St. Clair River

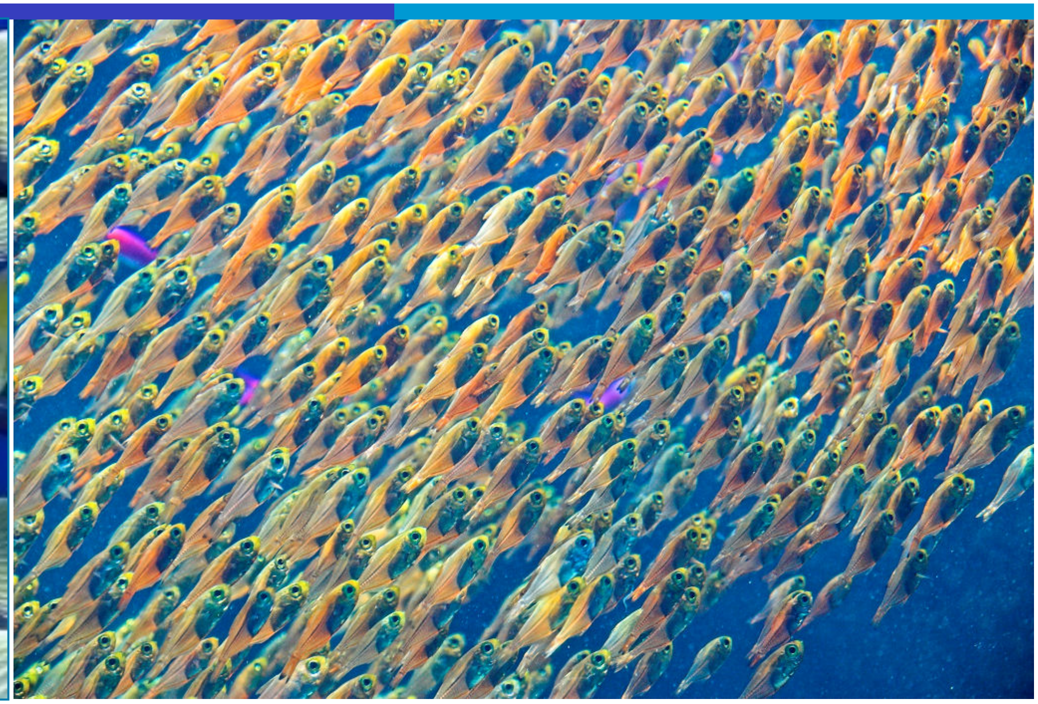
Underwater view of VIVACE cylinders

River deployment: 2 cylinders with PTC

Open-water 2-cylinder testing



III. Research: Vision and goals

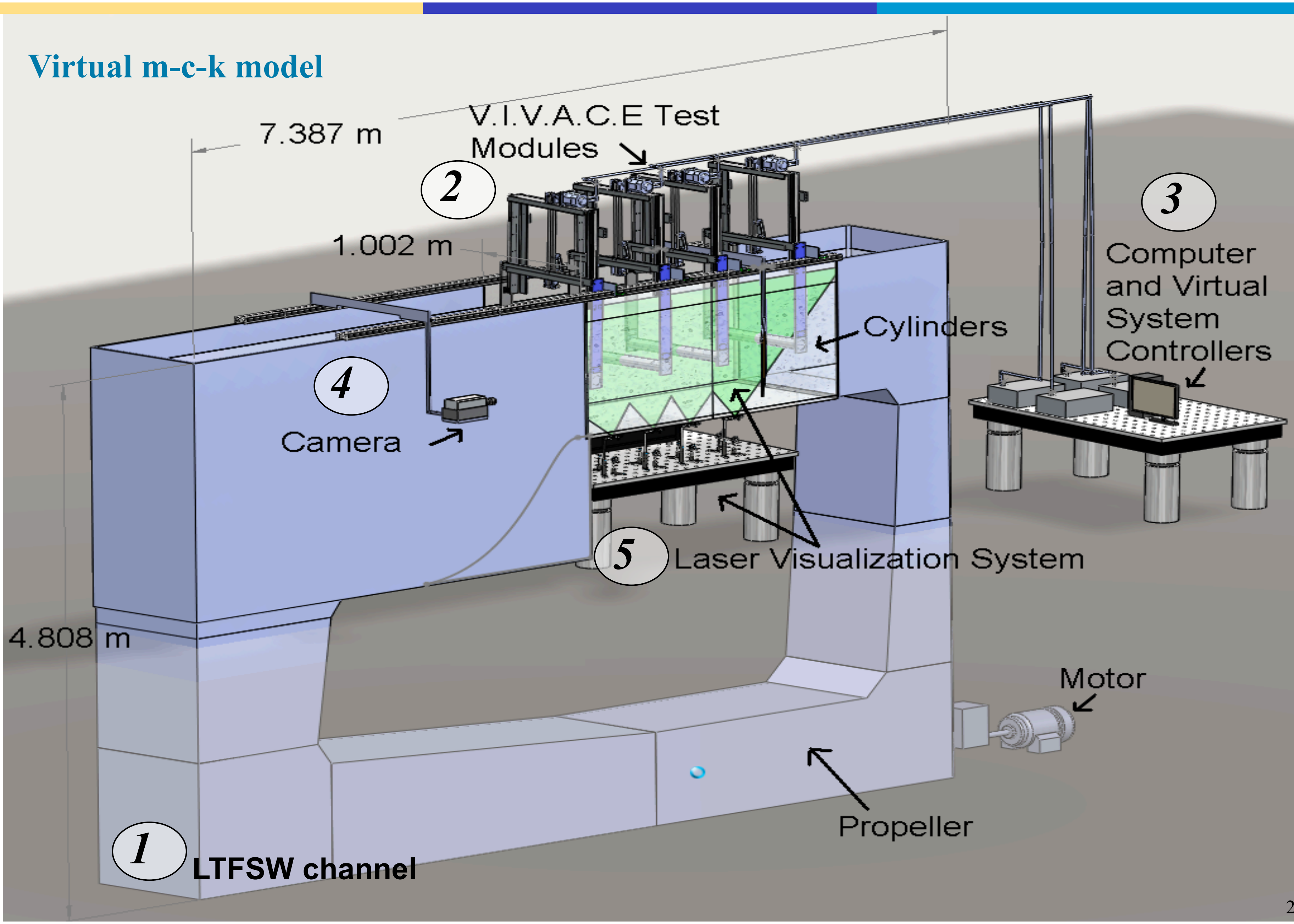
G1 Function like a school of fish, i.e. a 3-D device with component synergy stemming only from hydrodynamic interaction

G2 Operate efficiently at four scales with speeds as low as 0.5knots

G3 Be environmentally compatible.

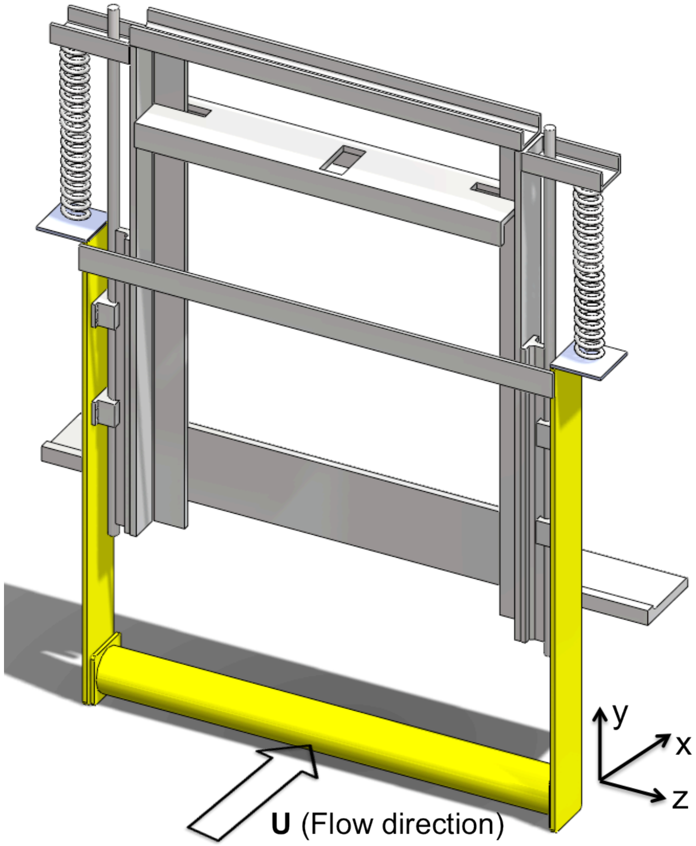
G4 Generate electricity at a competitive cost.

Objective #1: Integrated PTO & V_{mck}

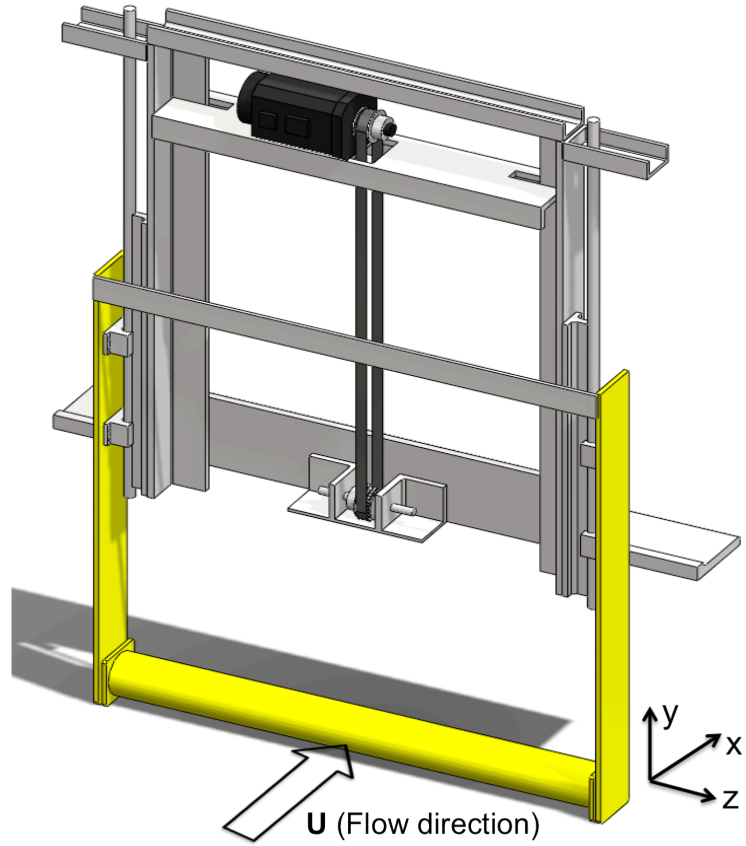


Physical & Virtual VIVACE

Schematic of physical VIVACE converter



Schematic of virtual VIVACE converter



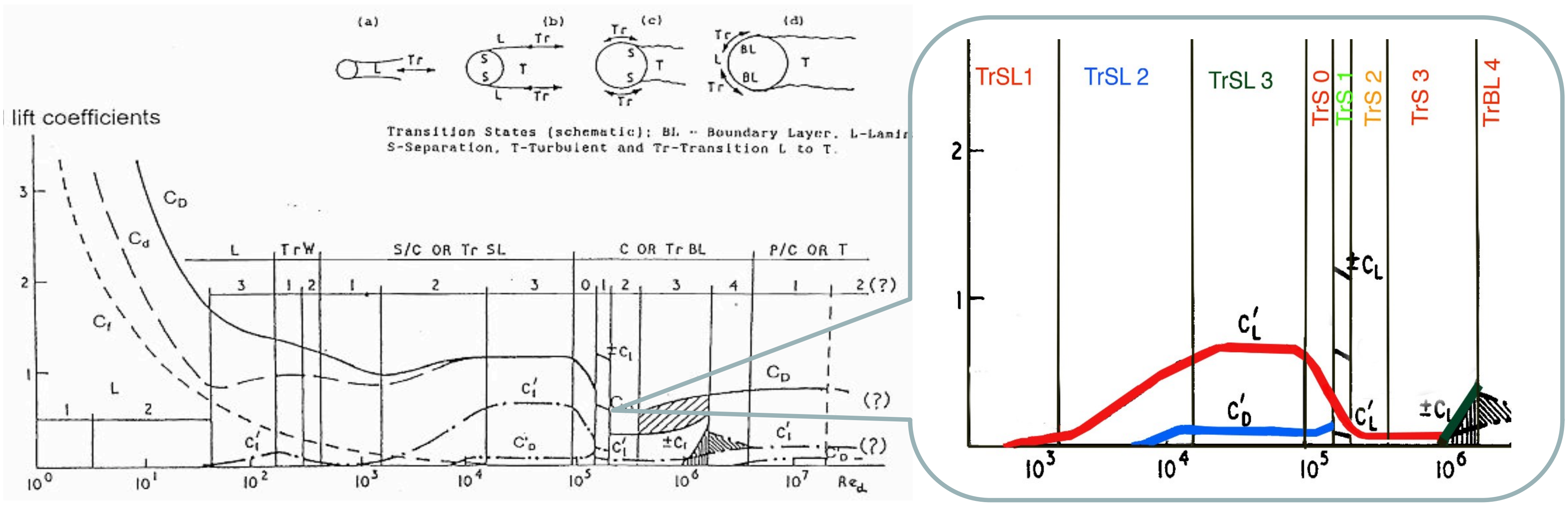
$$m\ddot{y} + (c_{bearing} + c_{harn})\dot{y} + k_{virual}\, y = f_{fluid}(t)$$

$$F_{motor} = f(\dot{y}) - c_{virtual}\dot{y} - k_{virtual}\, y$$

$$m\ddot{y} + c_{bearing}\dot{y} = f_{fluid}(t) + F_{motor}$$

Objective #2: Hydrokinetic to Mechanical

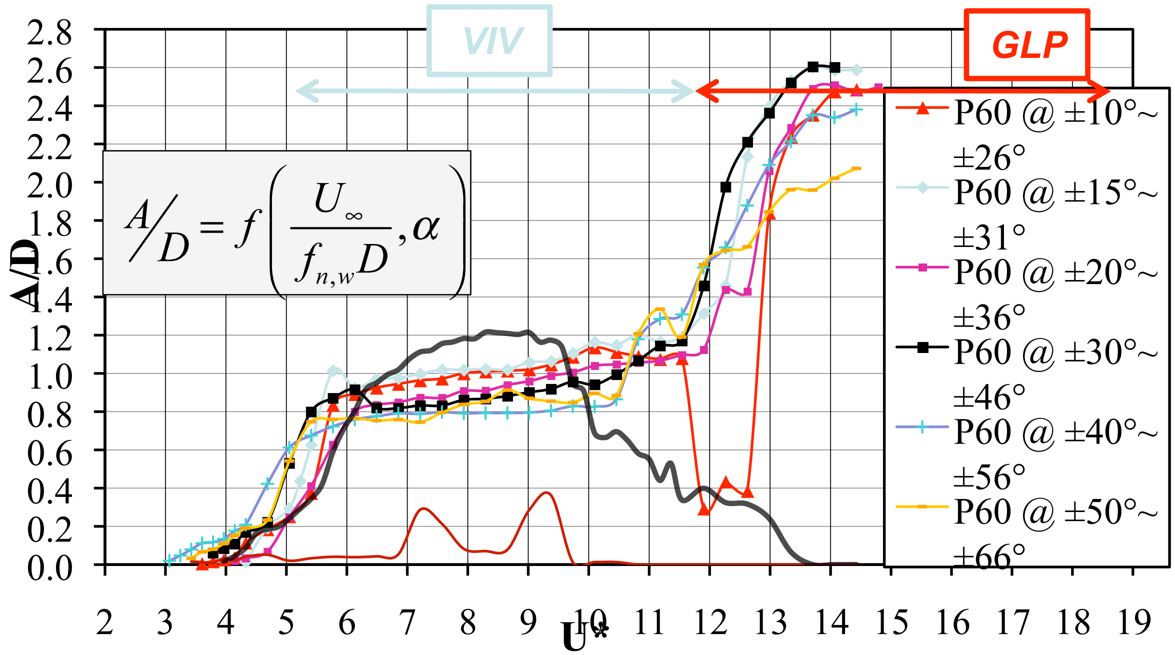
Expand the high lift regime TrSL3

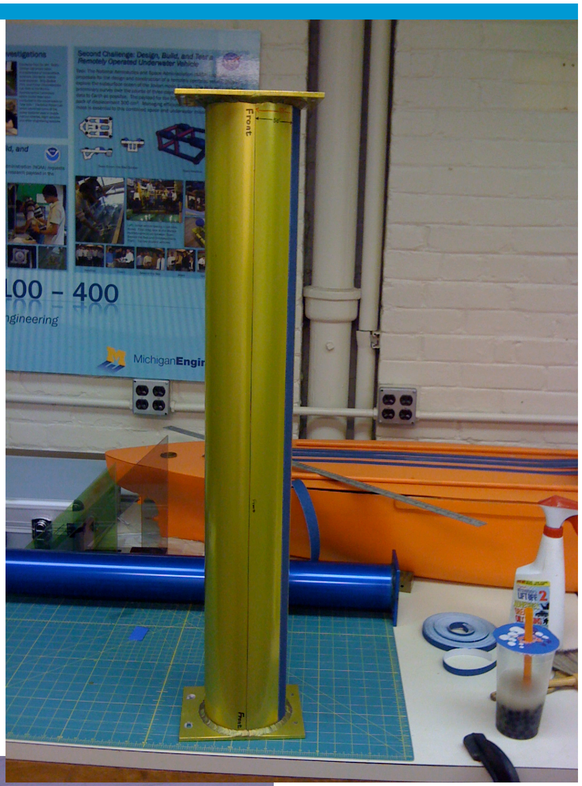


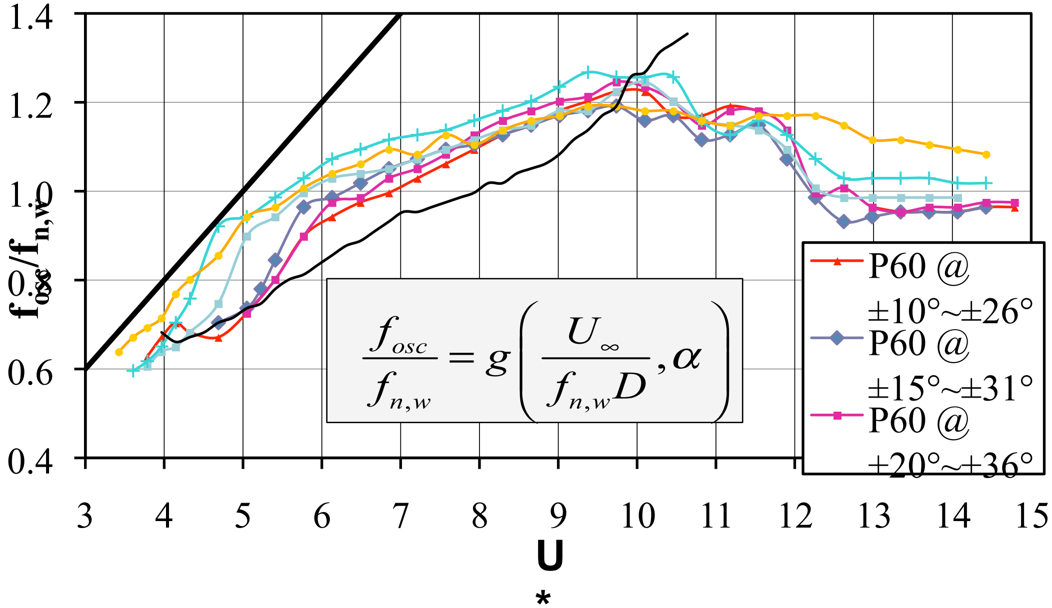
Drag and lift coefficient vs. Re (Zdravkovich 1997)

Reynolds number lower limit range < Re < upper limit range	Name of the regime	Characteristic feature
1×10^3- 2×10^3 < Re < 2×10^4- 4×10^4	TrSL2	Formation of transition vortices in free shear layer
2×10^4- 4×10^4 < Re < 1×10^5- 2×10^5	TrSL3	Fully turbulent shear layer
1×10^5 - 2×10^5< Re < 3.5×10^5- 6×10^6	TrBL	

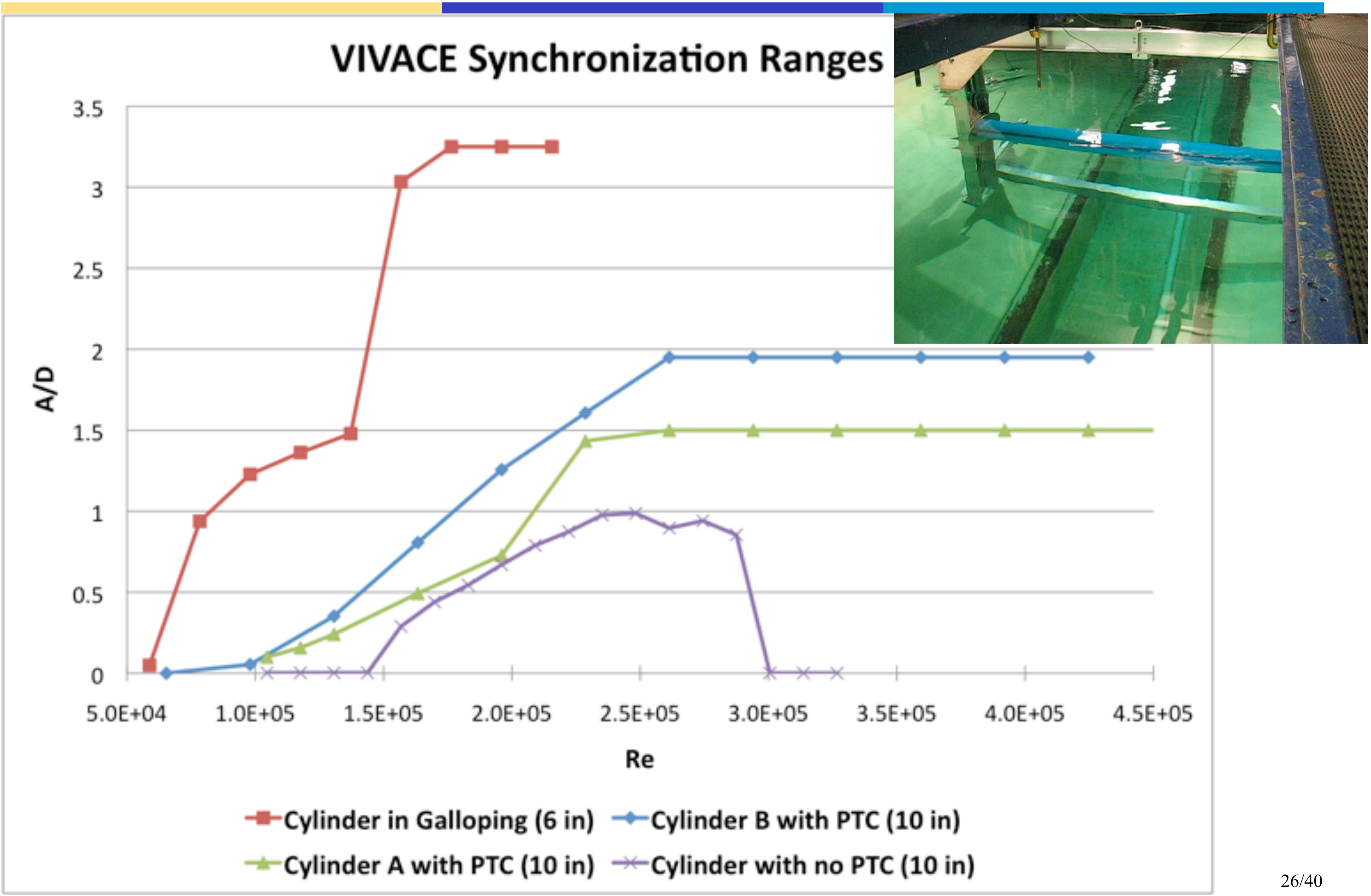
Expand synchronization range $U_r = U_{cur}/(f_{n,w}D)$







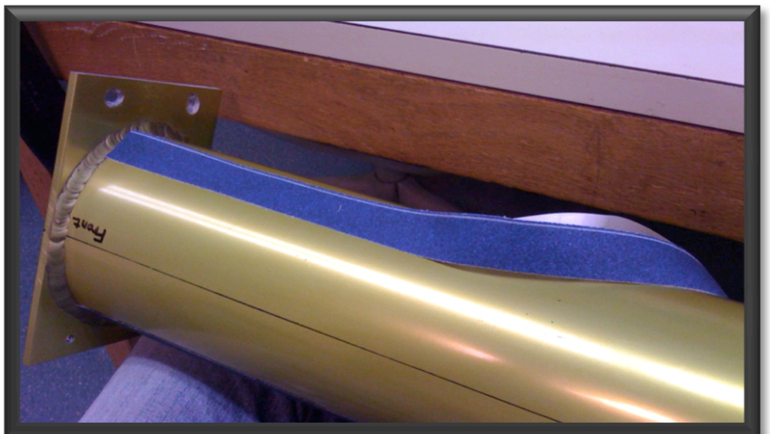
Maintain VIV in the transition region



Objective #3: Passive turbulence control

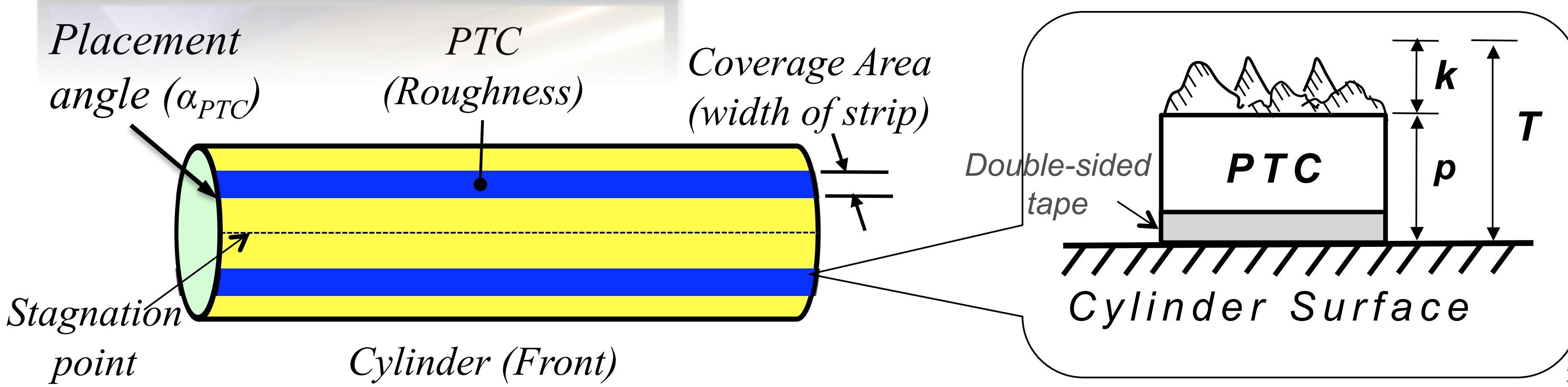
Mechanics of PTC

- Trip the boundary layer.
- Set the correlation length.
- Introduce turbulence.

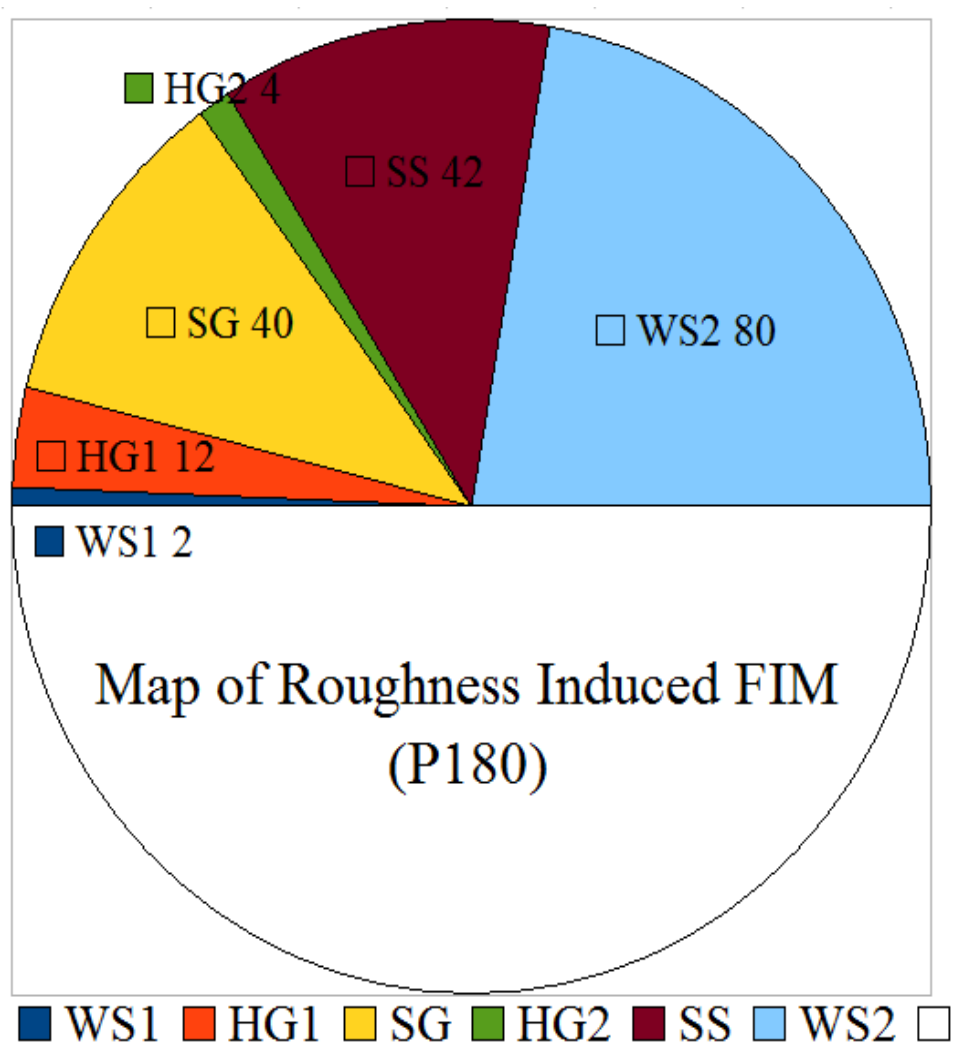


Major Parameters of PTC

- α_{PTC}, placement angle.
- Area coverage.
- k, Roughness grit size.
- T=k+p, PTC total height.



Map of PTC to FIM (P180)



- Half inch width, P180
- 6 Zones –WS1, HG1, SG, HG2, SS, WS2

Objective #4: Enhance vorticity or instability?

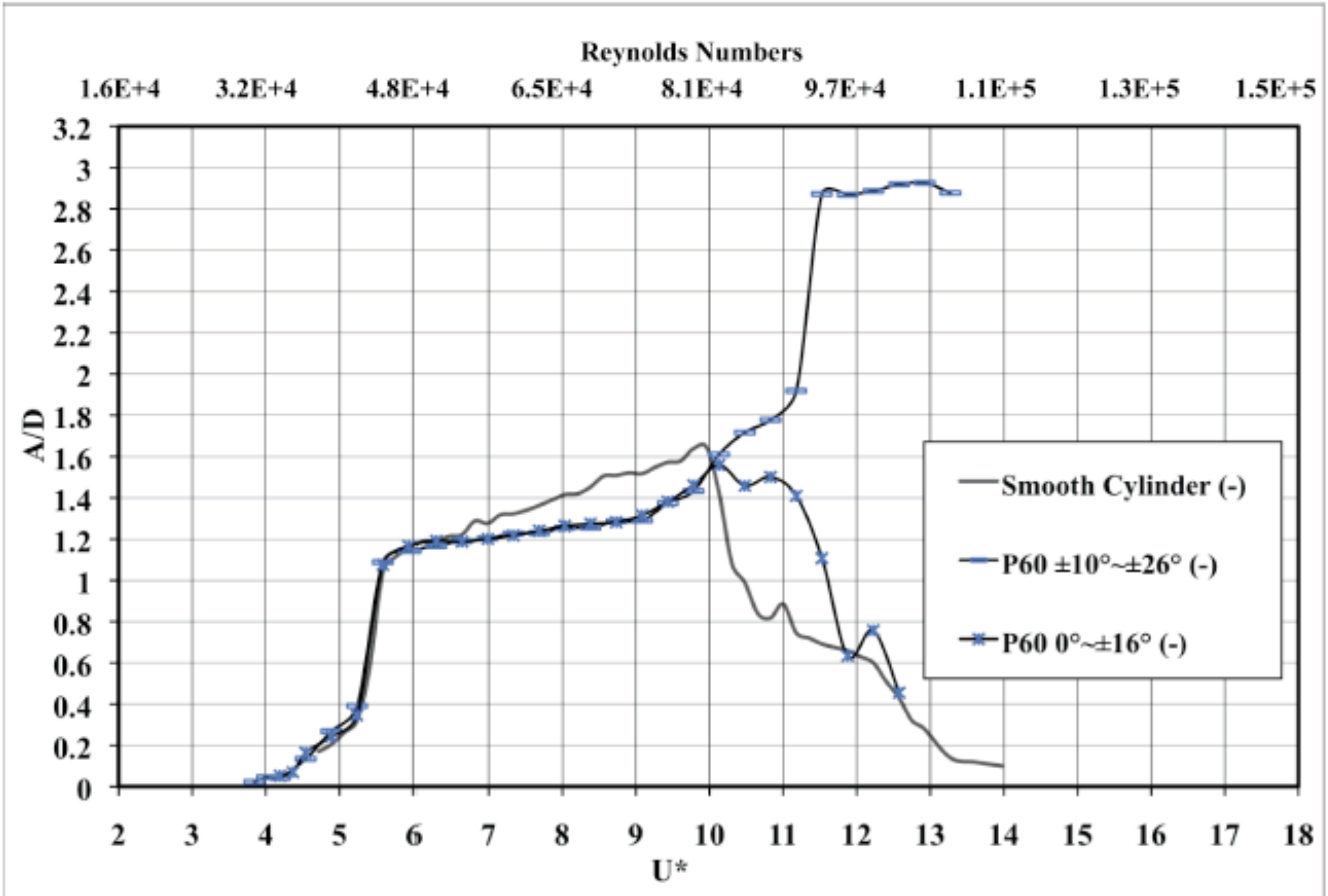
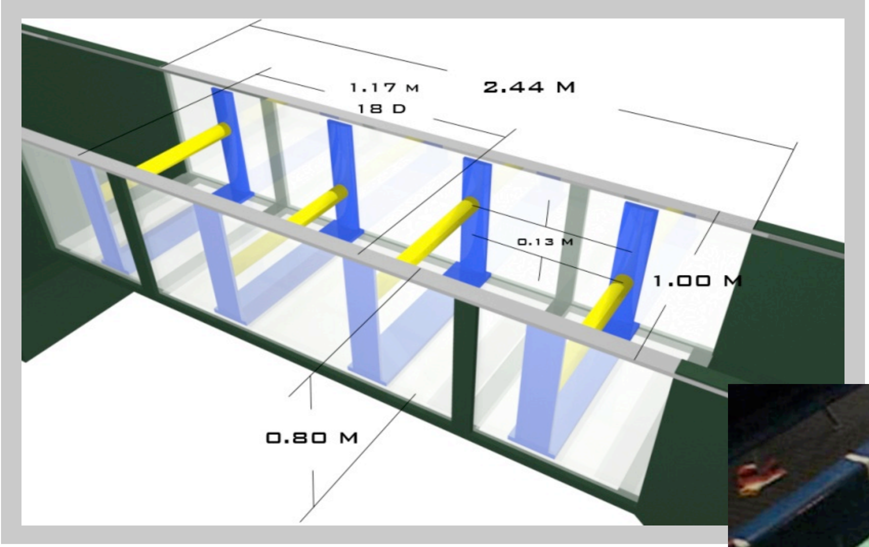


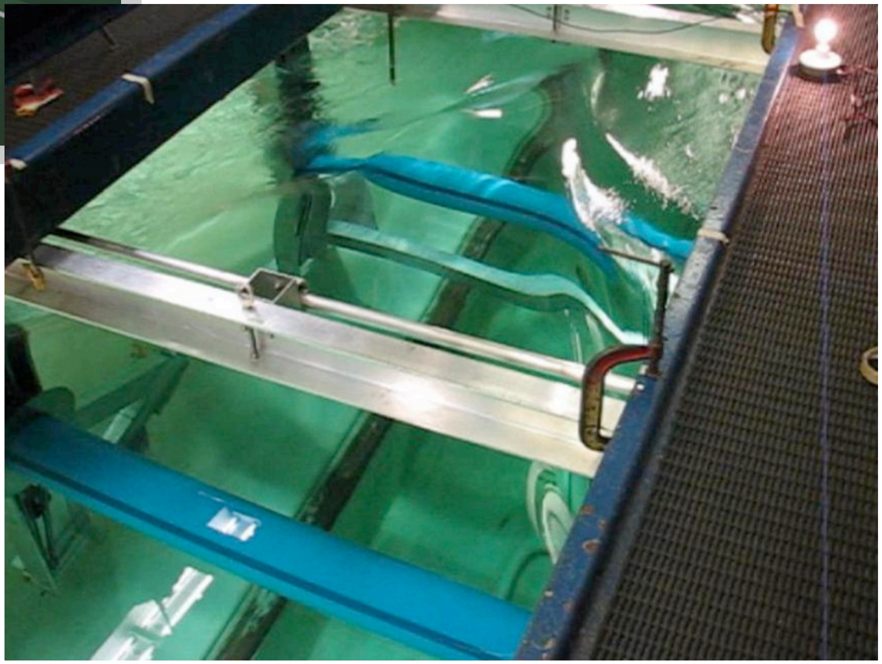
Figure 8(a). Amplitude plots showing critical strip locations for galloping.

Objective #5: Improve cylinder interaction

Four in the channel



Two in the towing tank



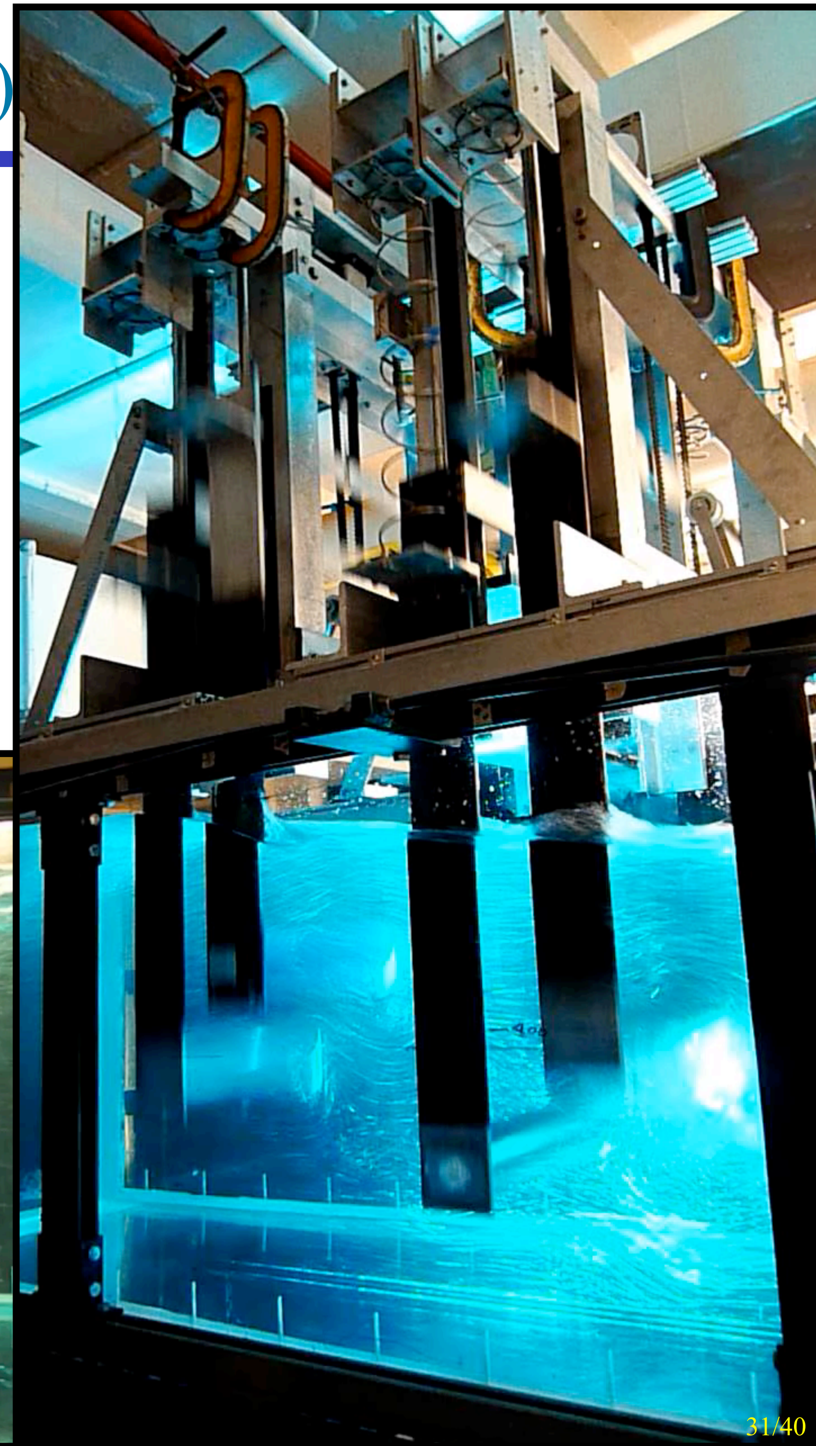
Two in the St. Clair River

Improve cylinder interaction (cont.)

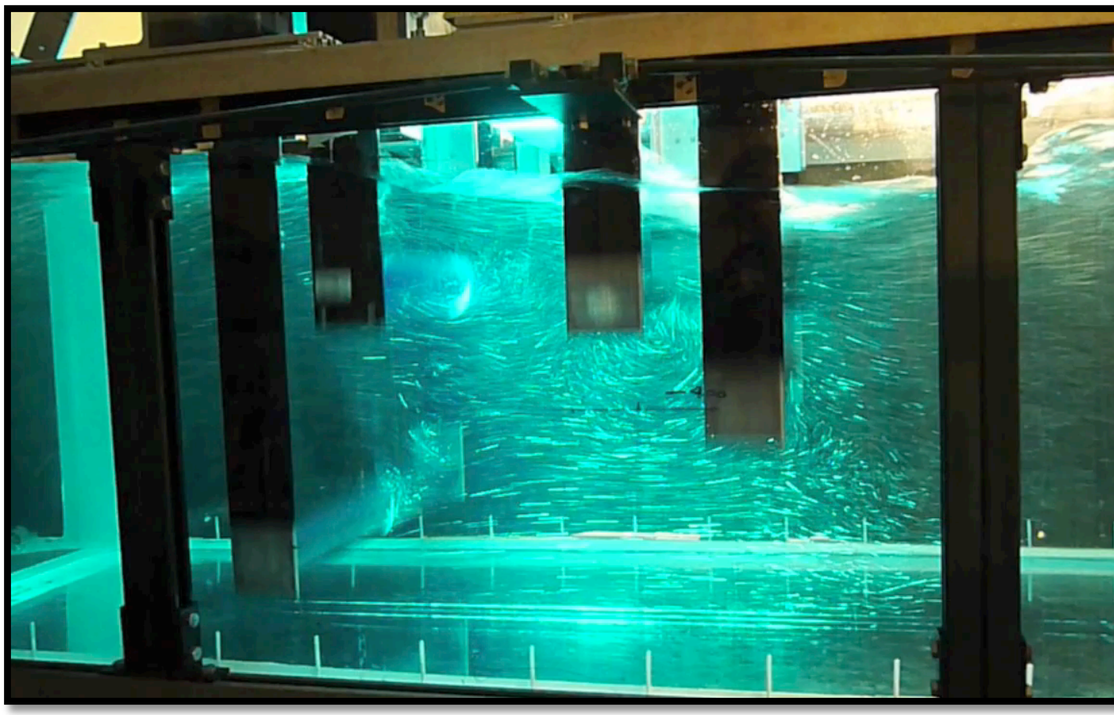
Four cylinders in the channel

Center to Center distances:

- 1 to 2: 1.95 Diameters
- 2 to 3: 3.95 Diameters
- 3 to 4: 1.63 Diameters

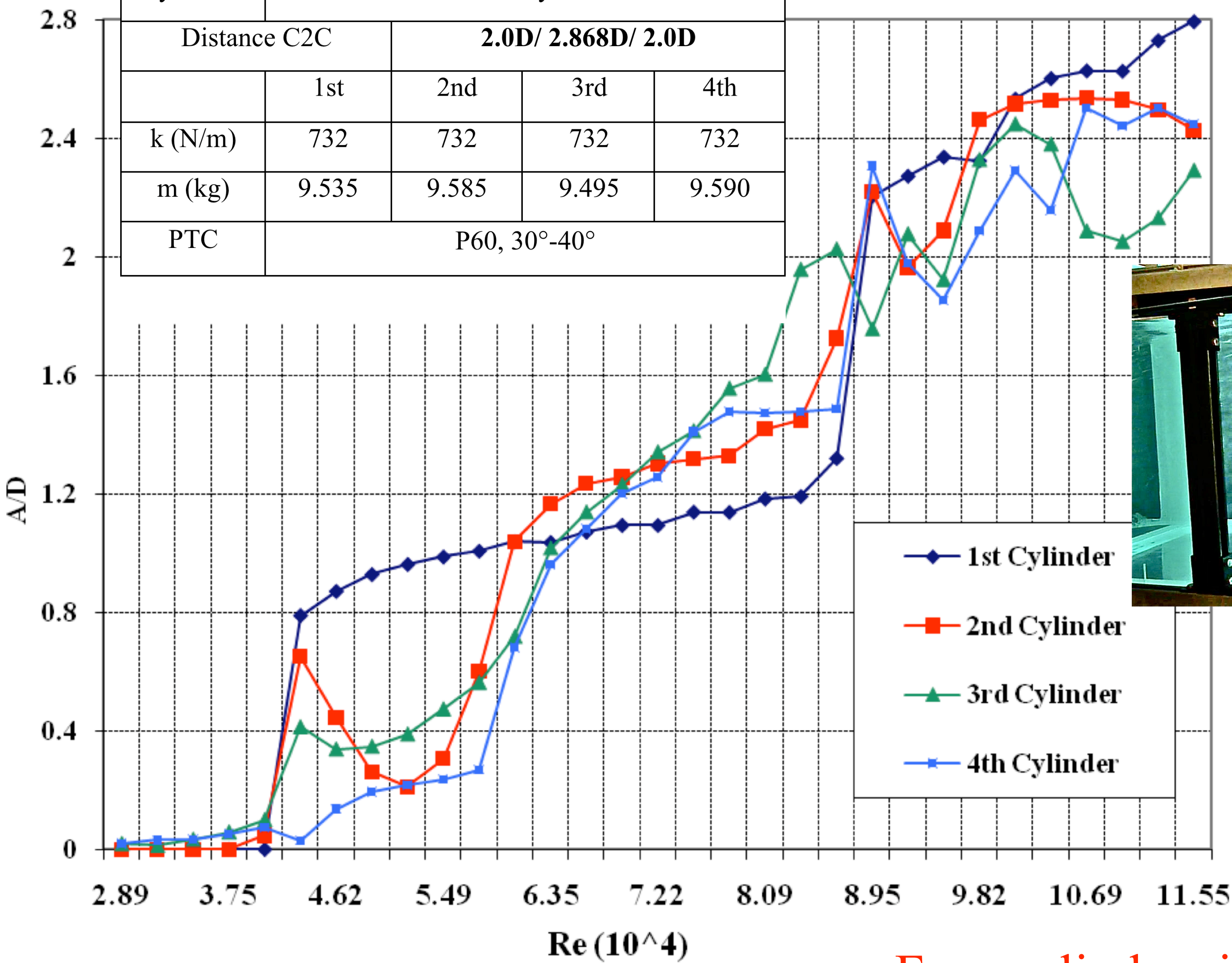


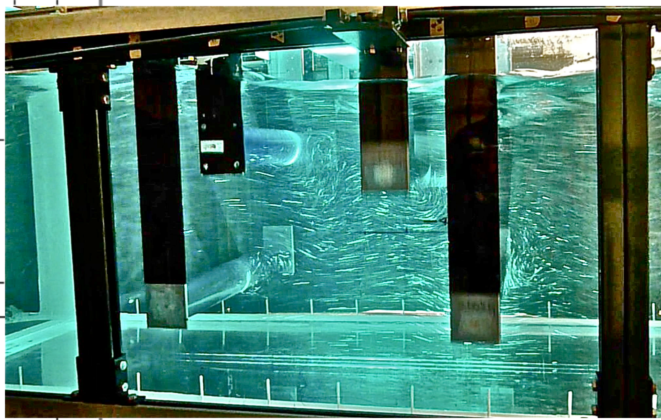
Cylinder spacing robustness



Improve cylinder interaction (cont.)

Cylinders	D3.5"- 4 cylinders			
Distance C2C		**2.0D/ 2.868D/ 2.0D**		
	1st	2nd	3rd	4th
k (N/m)	732	732	732	732
m (kg)	9.535	9.585	9.495	9.590
PTC	P60, 30°-40°			





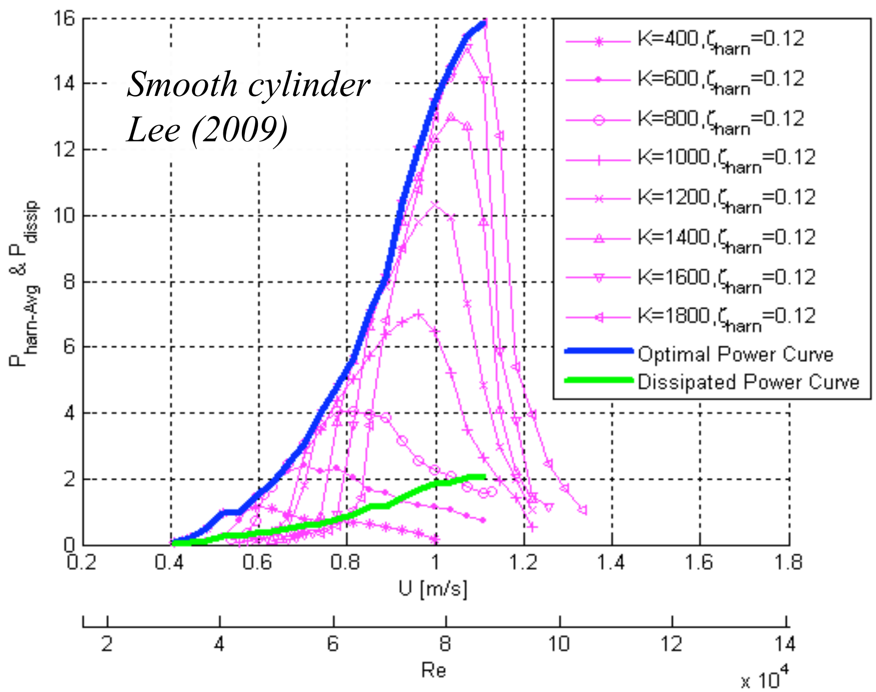
Four cylinders in the channel

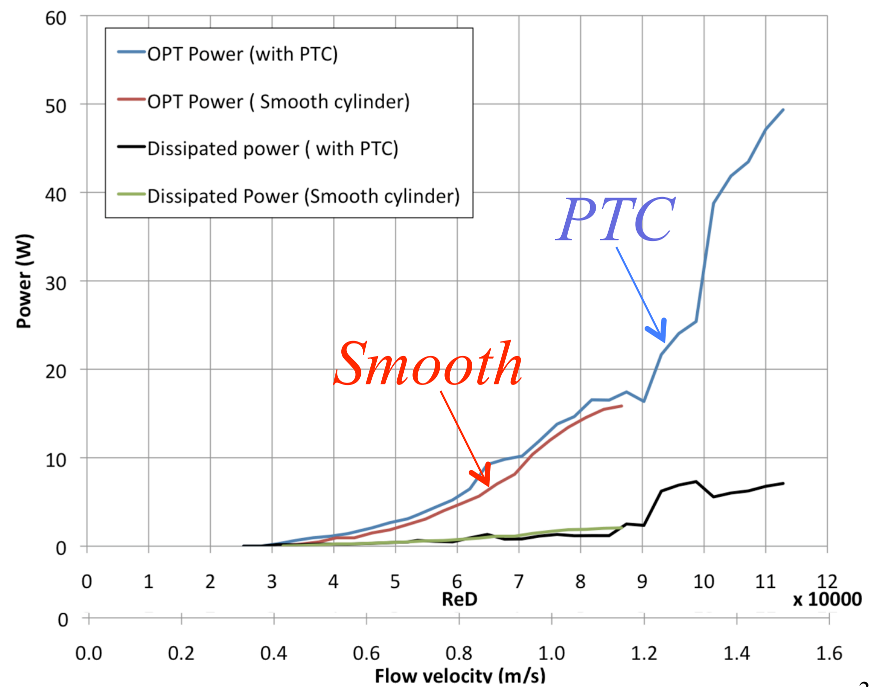
Objective #6: Increase power density

This is a hydrodynamic design issue: complexity vs. power density

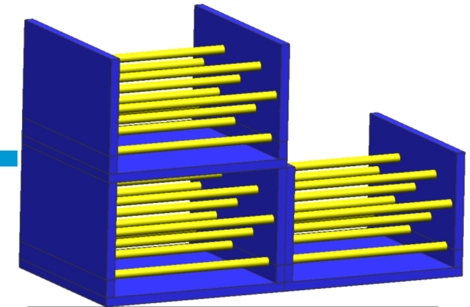
From: 51 W/m³ at 3 knots 5″ cylinder
To: 239 W/m³ at 3 knots 5″ cylinder
To: 341 W/m³ at 3 knots 3.5″ cylinder
To: 2,728 W/m³ at 6 knots 3.5″ cylinder

Diesel engines: 25,000 W/m³

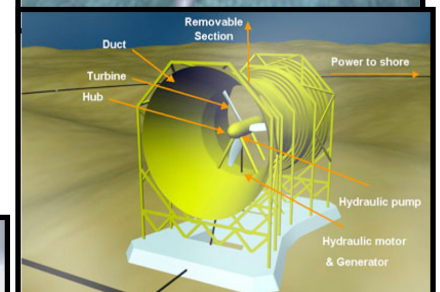


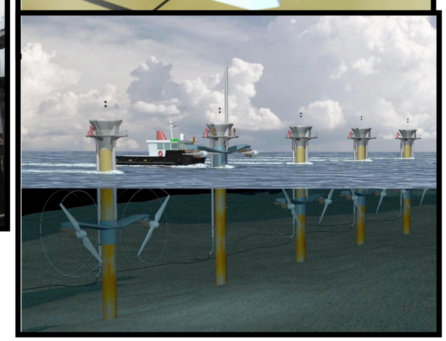


Benchmark: Power density

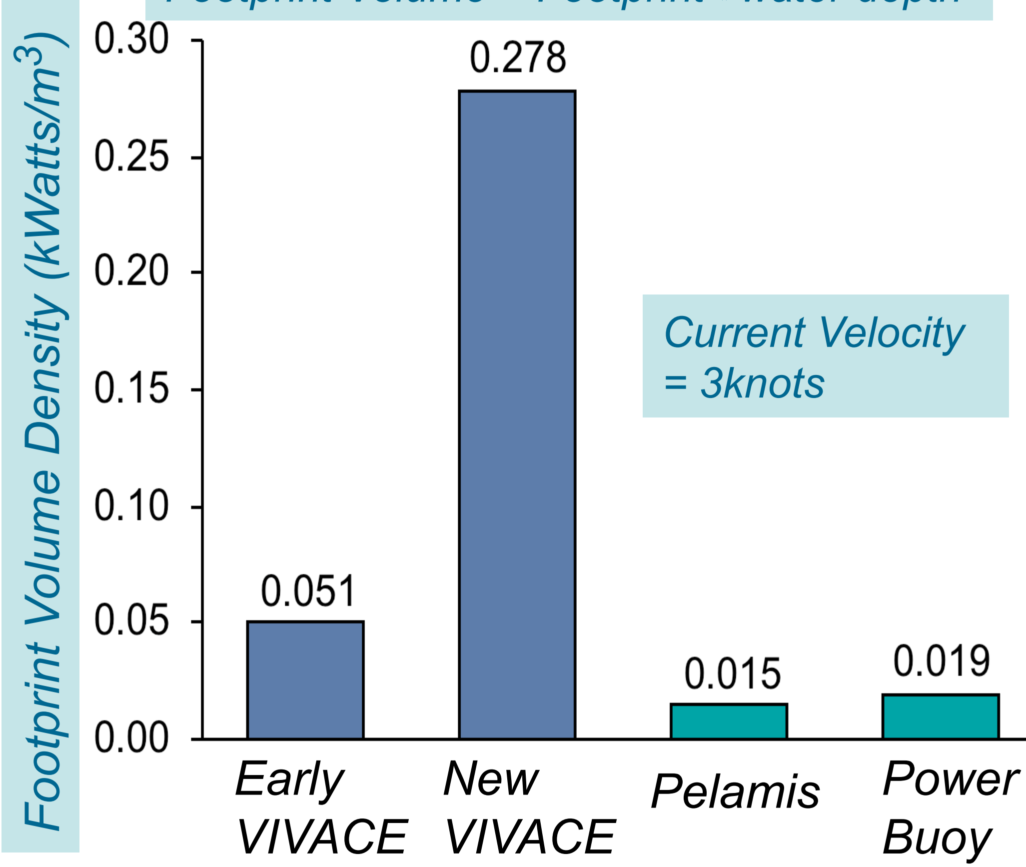


$$\frac{\text{VIVACE}}{\text{Wind}} > 14{,}600$$





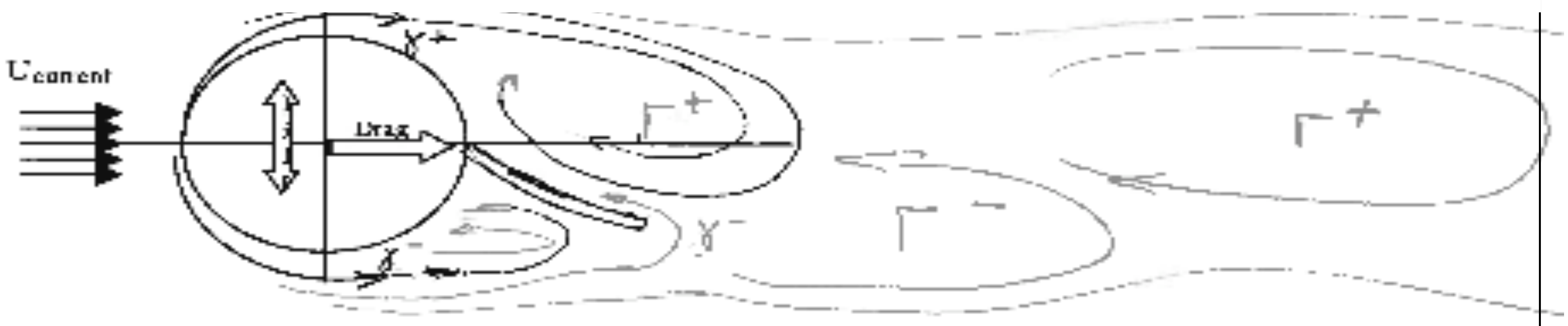
*Footprint Volume = Footprint * water depth*

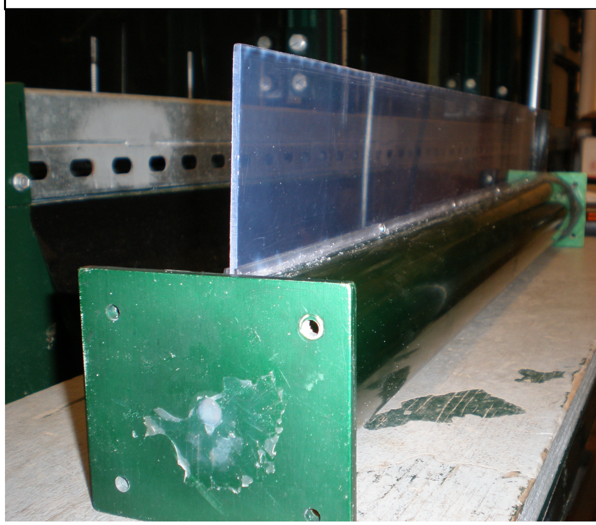


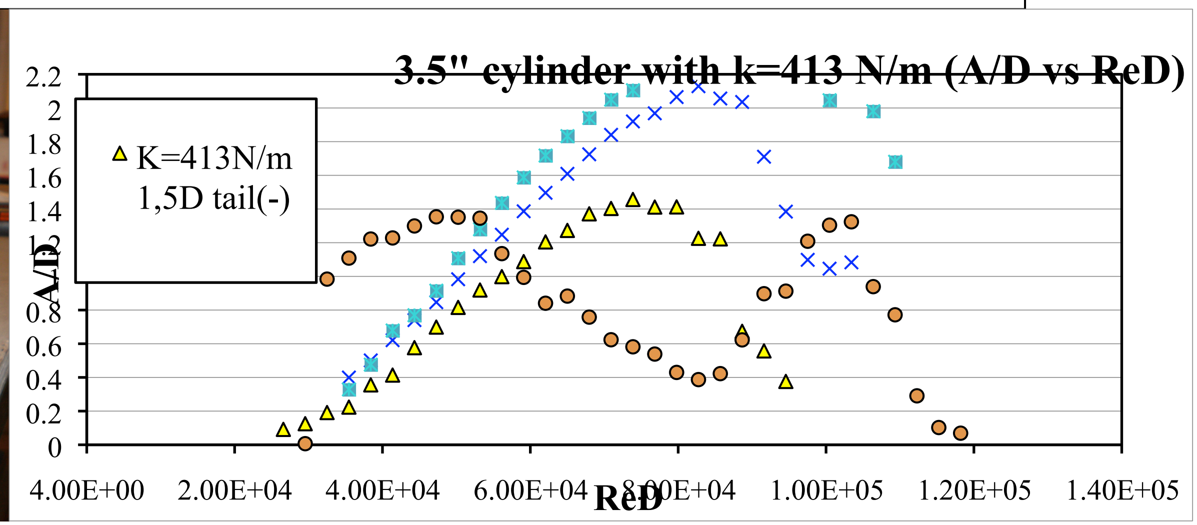
Objective #7: Fish-tail kinematics

Passive fish tail

Tails and splitter plates







Powerful but not a research priority of MRELab

Objective #8: Improve research tools

Measurements:

•Channel •Towing tank •St. Clair River

To identify new phenomena and their parametric dependence

Increase test section depth from 80cm to 120+25cm

Increase A/D limit from 3 to 5.5 for D=3.5"

Flow visualization: Large FOV (von Karman-scale)

To describe new phenomena and their wake/vortex structures.

To identify source of oscillatory forces.

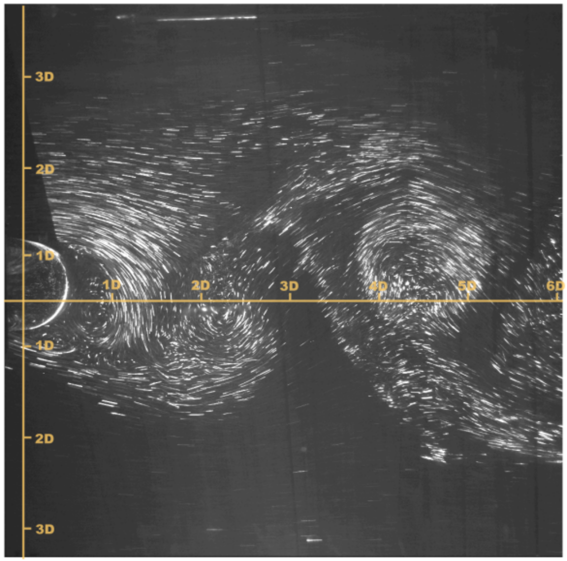
Flow visualization: Small FOV (Boundary layer-scale)

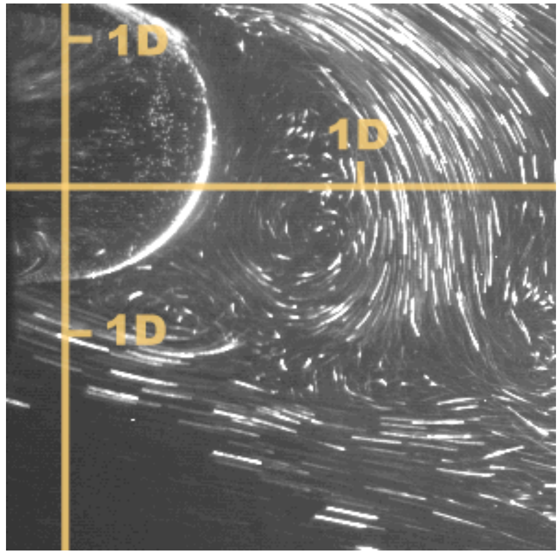
To understand the formation of the vortex structures and shear layers that cause these new phenomena.

CFD simulations:

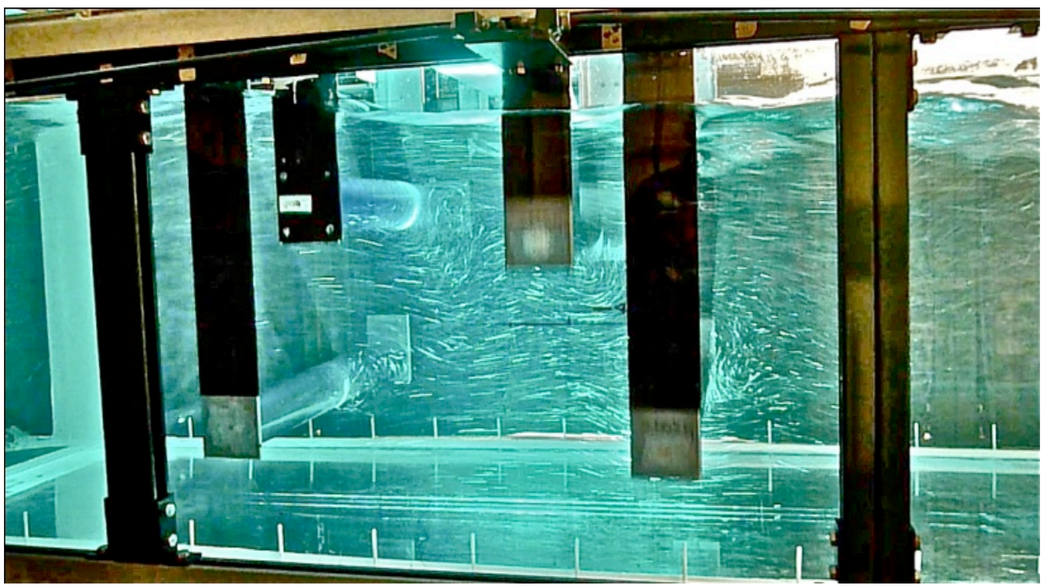
For comparison and possibly complementary data only.

Visualization: Large FOV





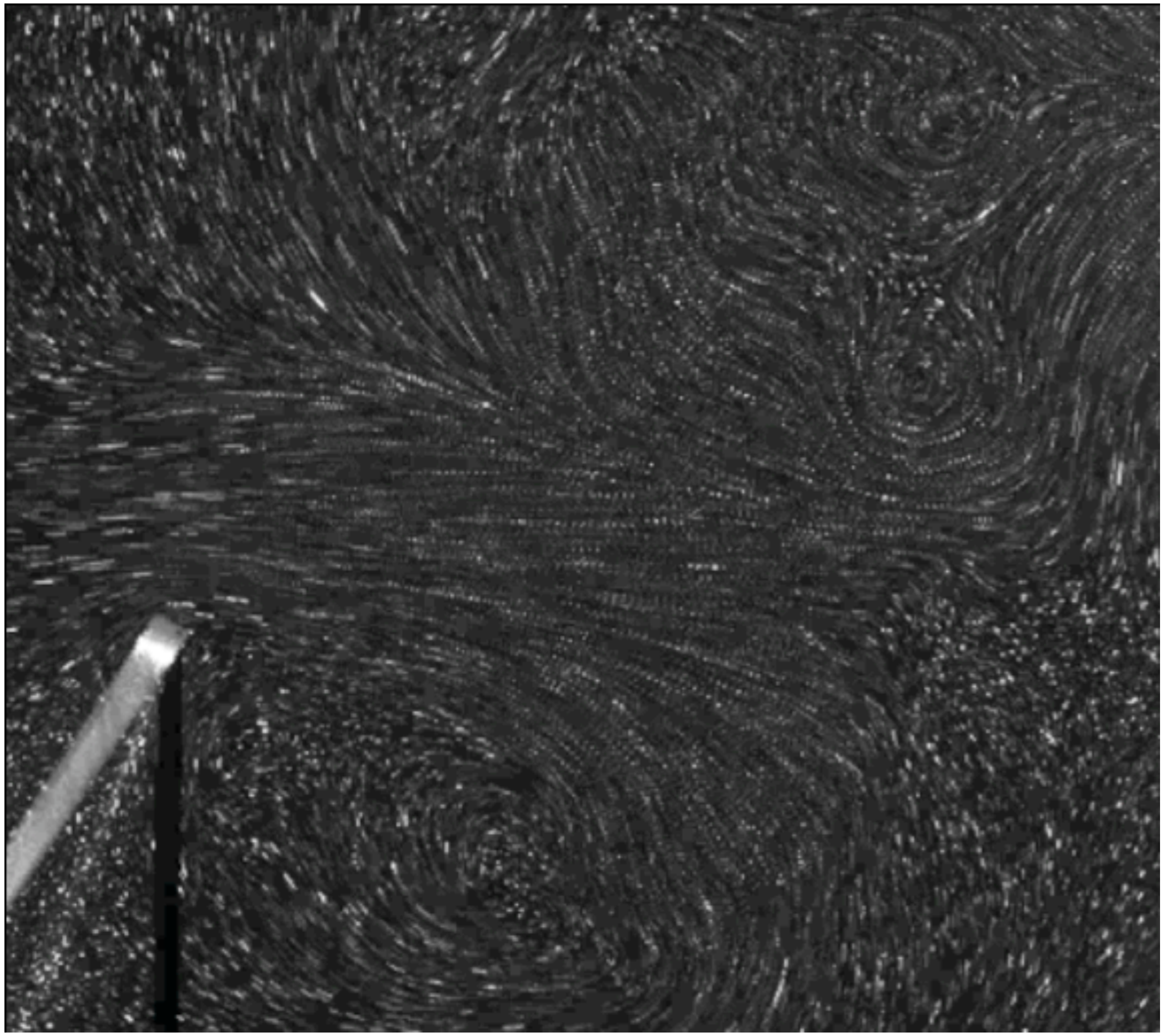
Single-body with broad-wake FOV: about 6*D; magnified on the right.



Multi-body with broad-wake FOV: about 15*D

Wake-structure scale with 32 frames/sec

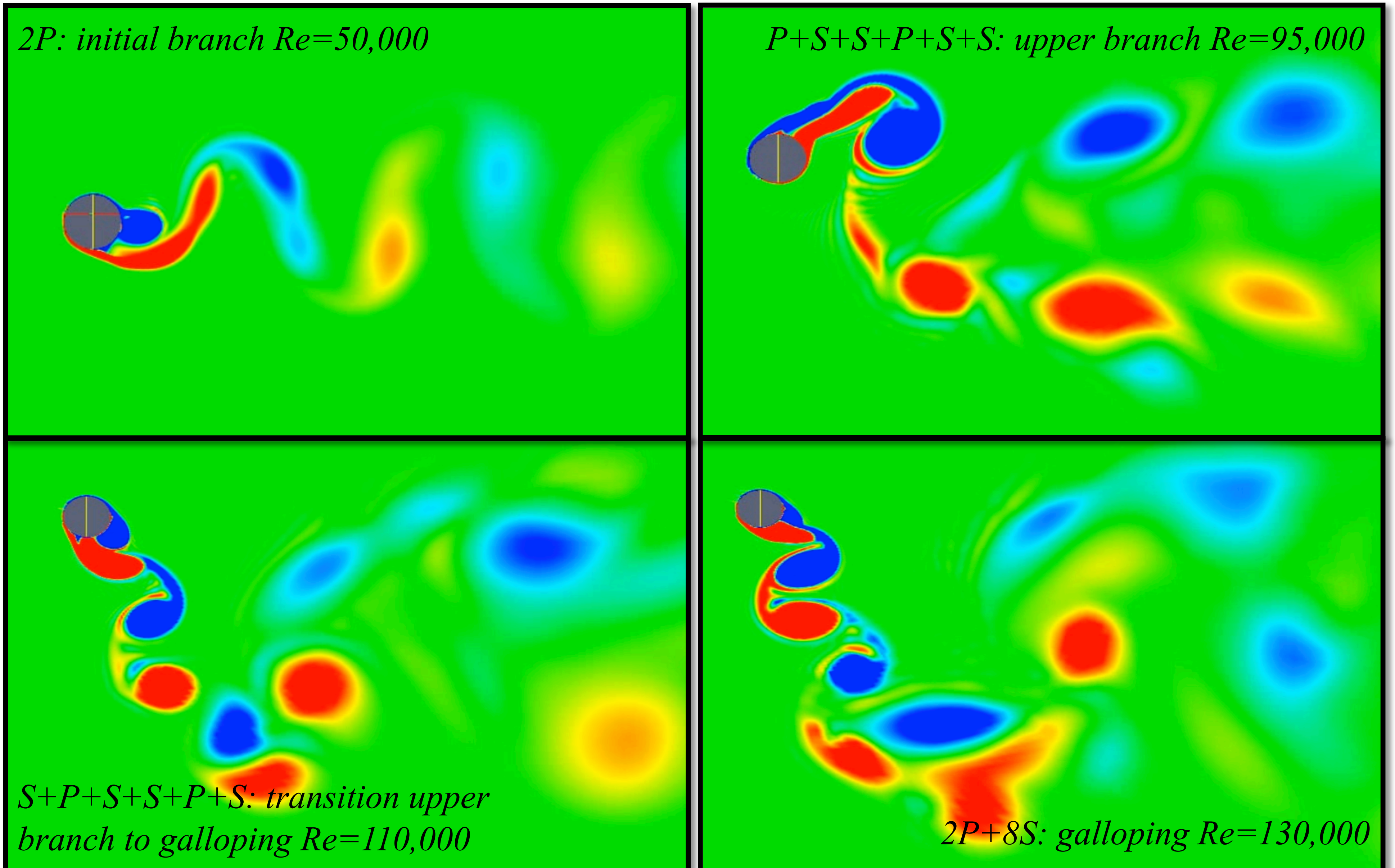
Visualization: Small FOV



Boundary layer scale with 1,000 frames/sec for PIV

CFD simulations

Cylinder with PTC in FIM at high Reynolds numbers



THANK YOU for your attention

Acknowledgements

National Science Foundation
WHERE DISCOVERIES BEGIN

DOD

DOE

NAVFAC
Naval Facilities Engineering Command

muci
MICHIGAN UNIVERSITIES COMMERCIALIZATION INITIATIVE

Michigan Engineering
Office of
Technology Transfer

Detroit/Wayne County
Port Authority

DTE Energy

Marine Renewable
Energy Laboratory
University of Michigan

VORTEX
HYDRO ENERGY