Buoy Arrays & Coastal OWC's for Wave Energy Extraction

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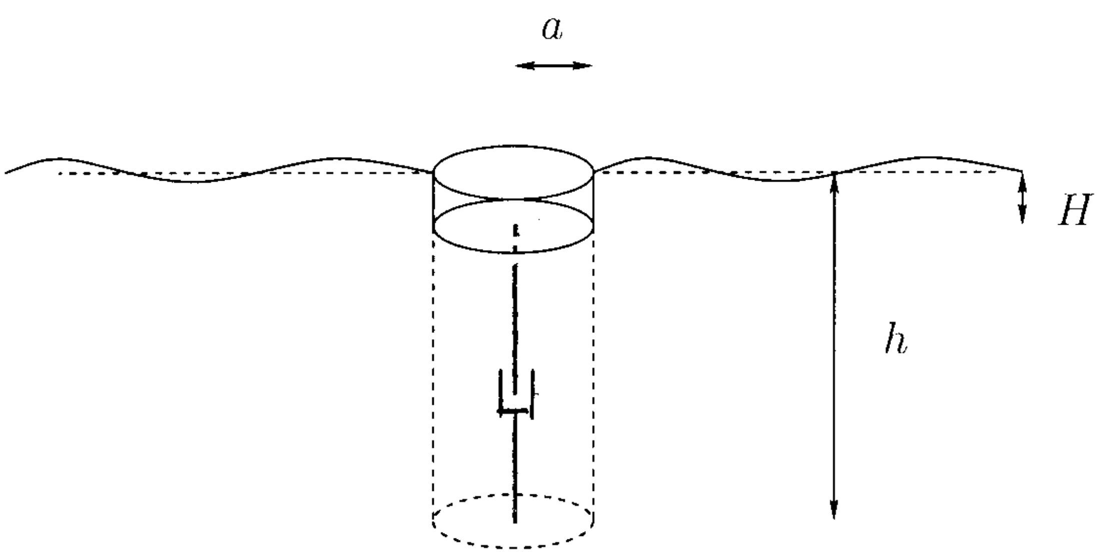
- Single Buoy
- Sparse Array of Buoys
- Compact Array of Buoys
- OWC on a coast

Background : single buoy



Extractor= force on buoy= $-\lambda_g \frac{\partial \zeta}{\partial t}$

λ_g=extraction coefficient

Power extraction

Force from PTO: $-i\omega\lambda_g\zeta$

Newton:

$$-\omega^2(M+\mu) = F^D - i\omega(\lambda+\lambda_g) + \pi a^2$$

Power extracted

$$P = \frac{(1/2)\lambda_g\omega^2|F^D|^2}{\omega^2(\lambda+\lambda_g)^2 + (\pi a^2 - \omega^2(M+\mu))^2}$$

Conditions for maximum extraction – impedance matching

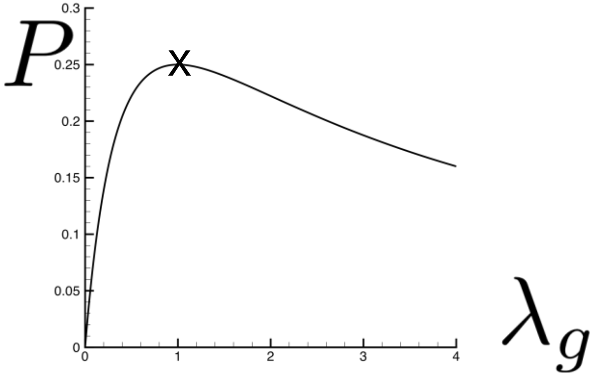
Resonance: $\pi a^2 - \omega^2 (M + \mu) = 0.$

Special extraction rate : $\lambda_g = \lambda$

Max power extraction and capture width

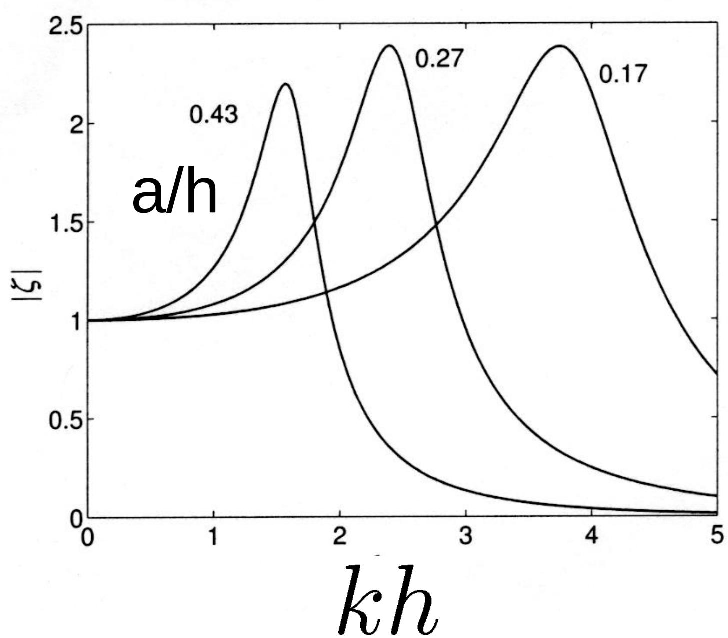
$$P = \frac{1}{2k} \rho g |A|^2 C_g, \quad kL = 1$$

after using Haskind theorem

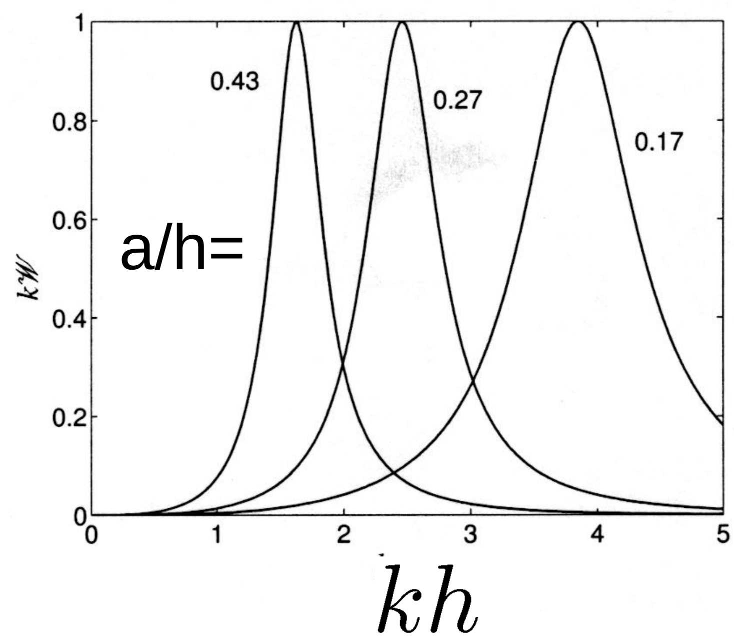


Size effect for a single buoy

ζ =buoy displacement



Capture width kL

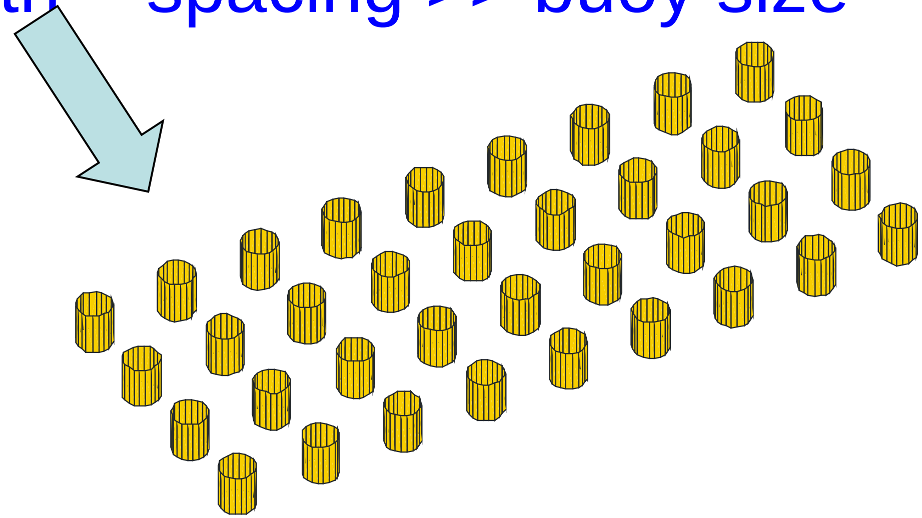


For $h = 15\ m$

a/h	0.43	0.27	0.17
$T(s)$	8	5	4

Sparse array

wavelength ~ spacing >> buoy size



For 100 % extraction by

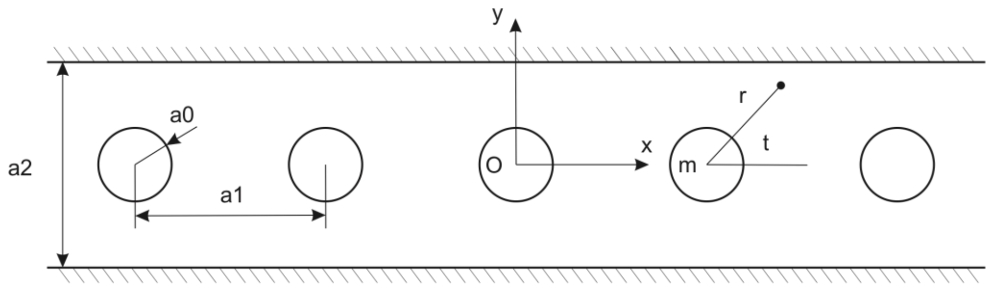
Single row: $W = 1/k$

Two rows: $W = 2/k$ Budal (1977)

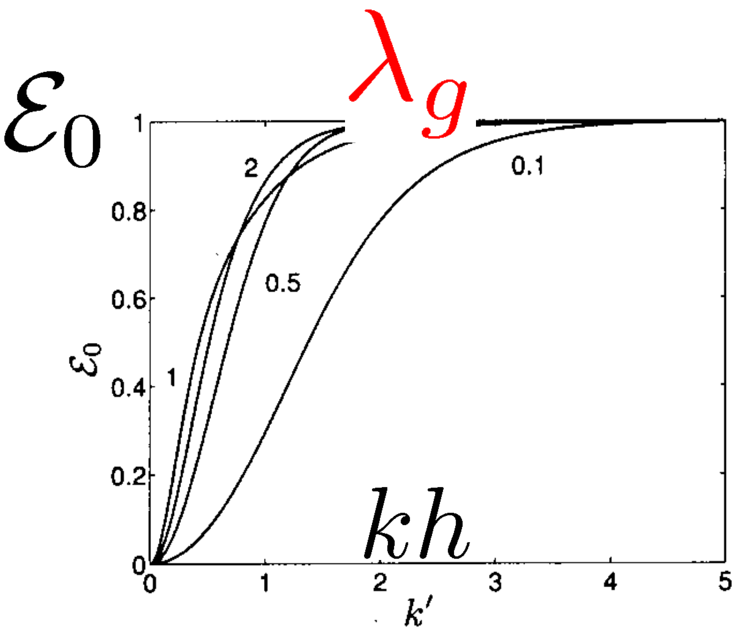
N rows: $N > 2 + 2kW/\pi$ Falnes(1984)

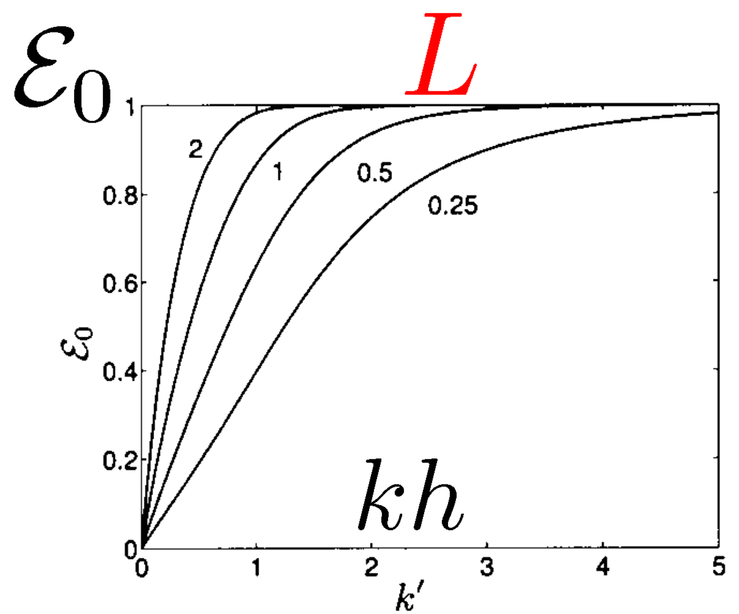
Away from Bragg Resonance

$$\text{Bragg resonance if } kd = n\pi$$



(Garnaud & Mei, 2009, submitted)





Effect of extraction rate and on Reflection and Transmission

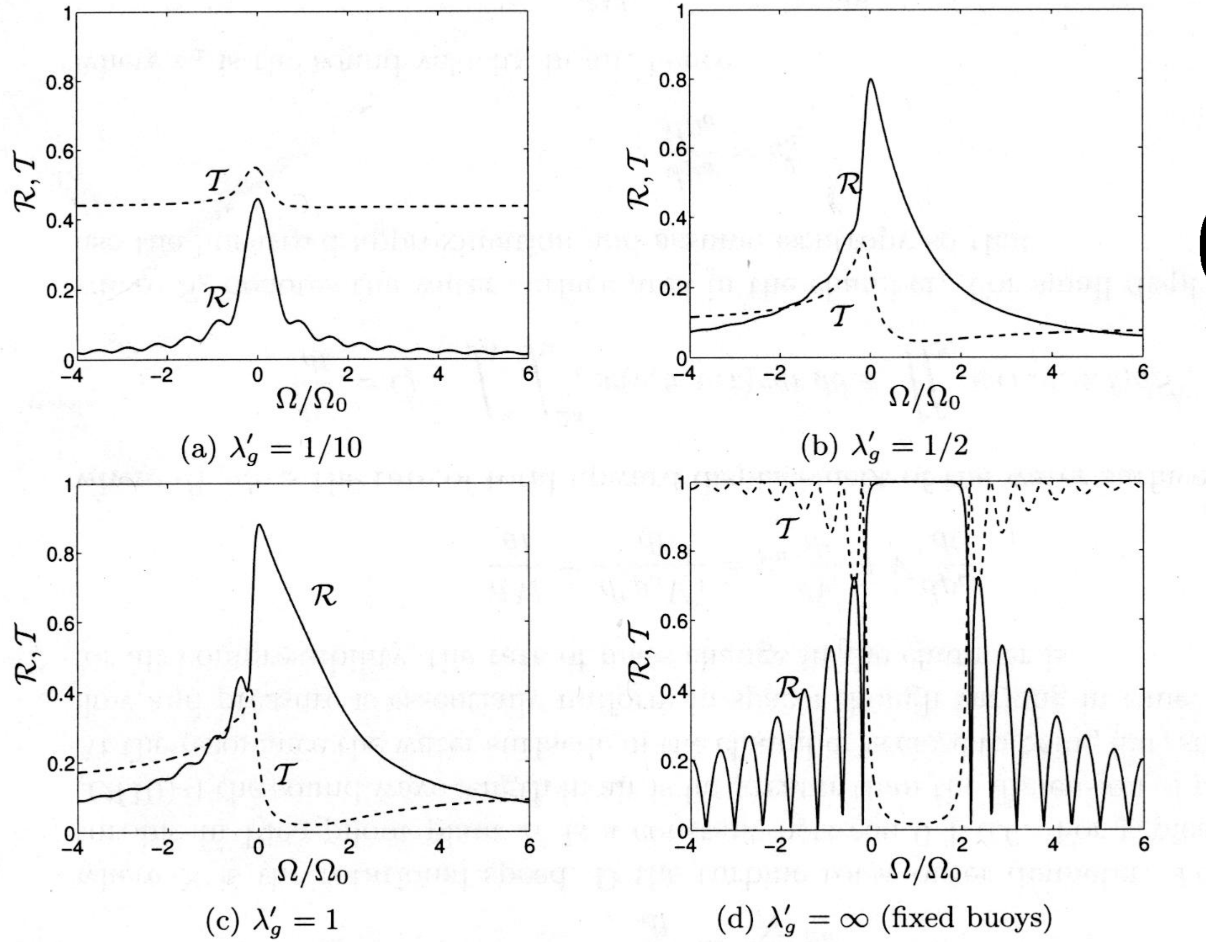
$$\lambda_g = 0.1, 0.5, 10, \infty$$

0.1

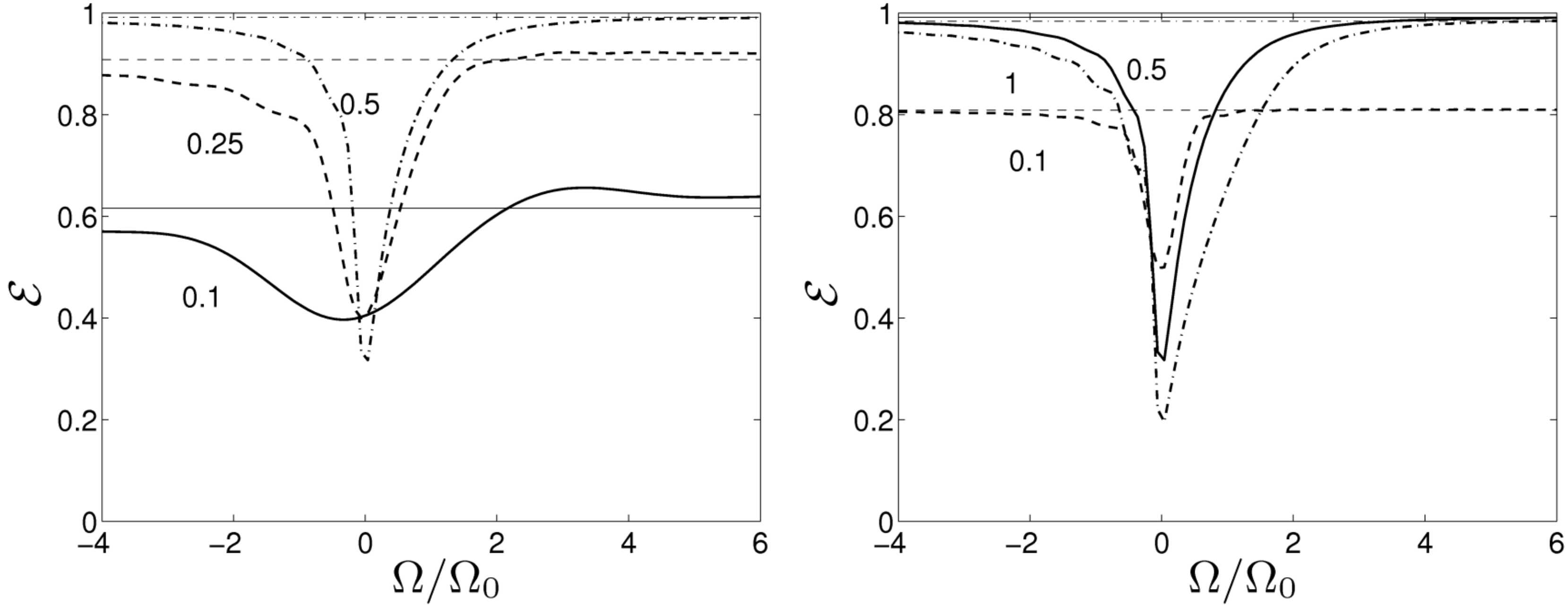
0.5

1.0

∞



Power absorption efficiency vs Detuning



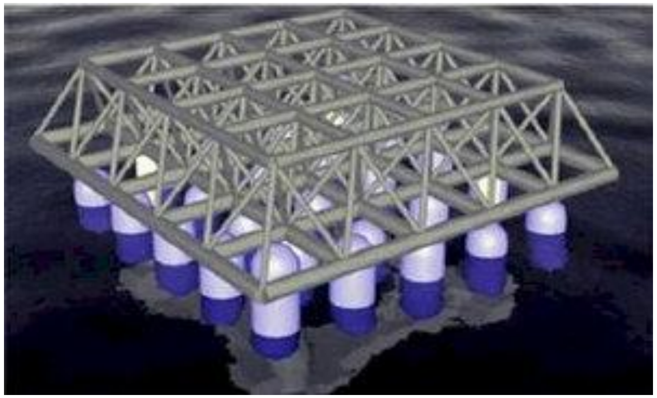
Fred Olsen (FO3)
ABB Power Systems,
Norway

36 m x 36 m,
2.5 MW
2.8 million Euro

Buoy size, spacing << wavelength

Boundary Condition on water surface

Solid fraction : $f = \frac{\pi a^2}{d^2}$



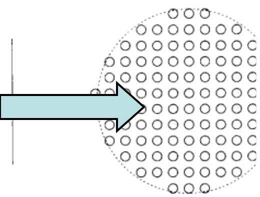
Not covered by buoys :

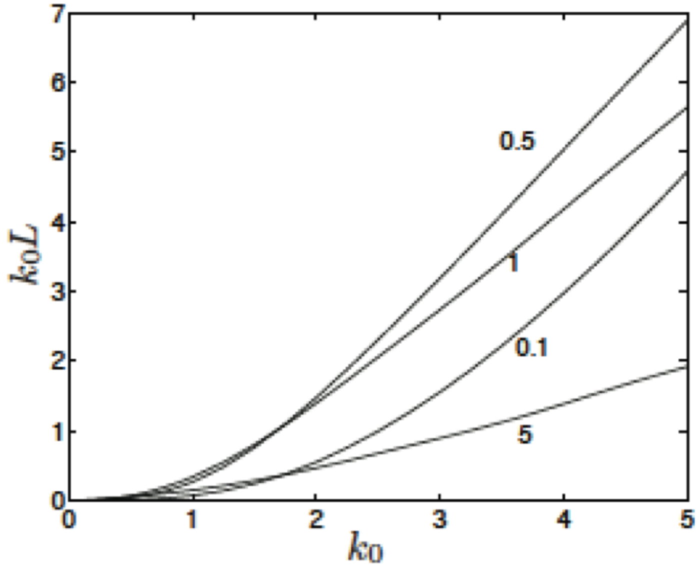
$$\frac{\partial \phi}{\partial z} - \frac{\omega^2}{g}\phi = 0, \quad z = 0.$$

Covered by buoys :

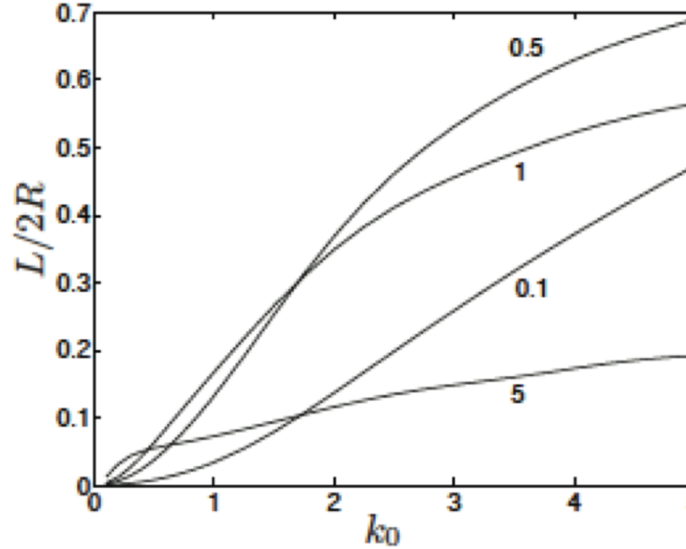
$$\frac{\partial \phi}{\partial z} - \frac{\omega^2}{g}\left[1 - f\left(\frac{i\lambda_g\omega}{1+i\lambda_g\omega}\right)\right]\phi = 0, \quad z = 0.$$

Assume negligible buoy inertia: $\frac{\omega^2 H}{g} \ll 1$

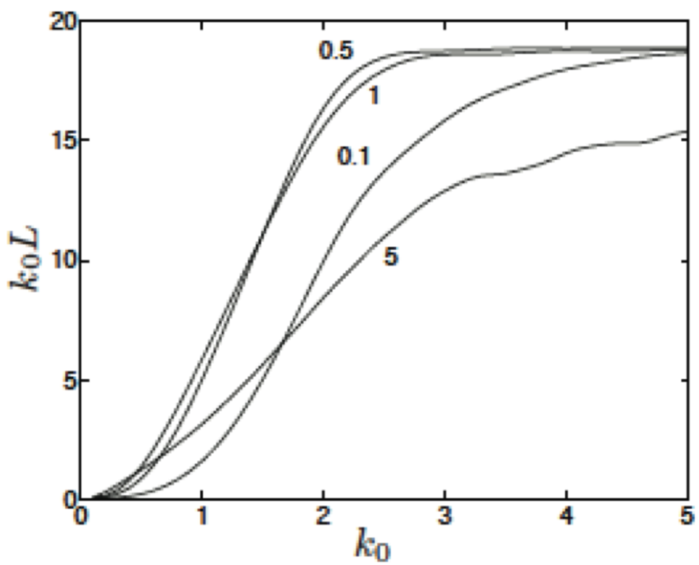




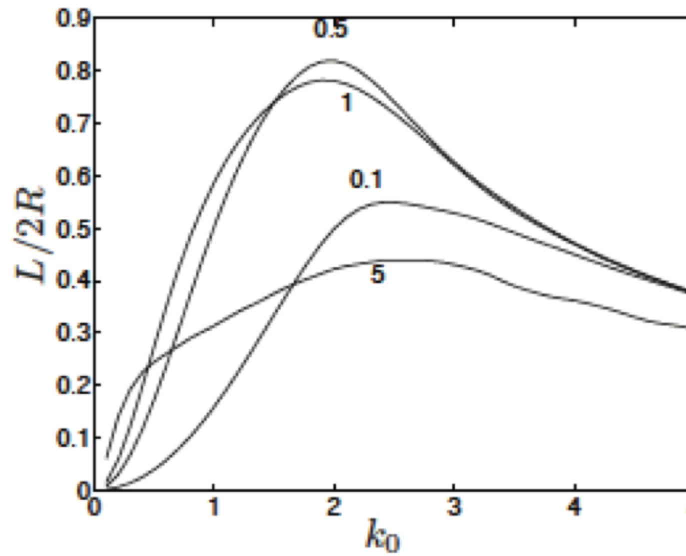
(a) $R = 1$



(b) $R = 1$

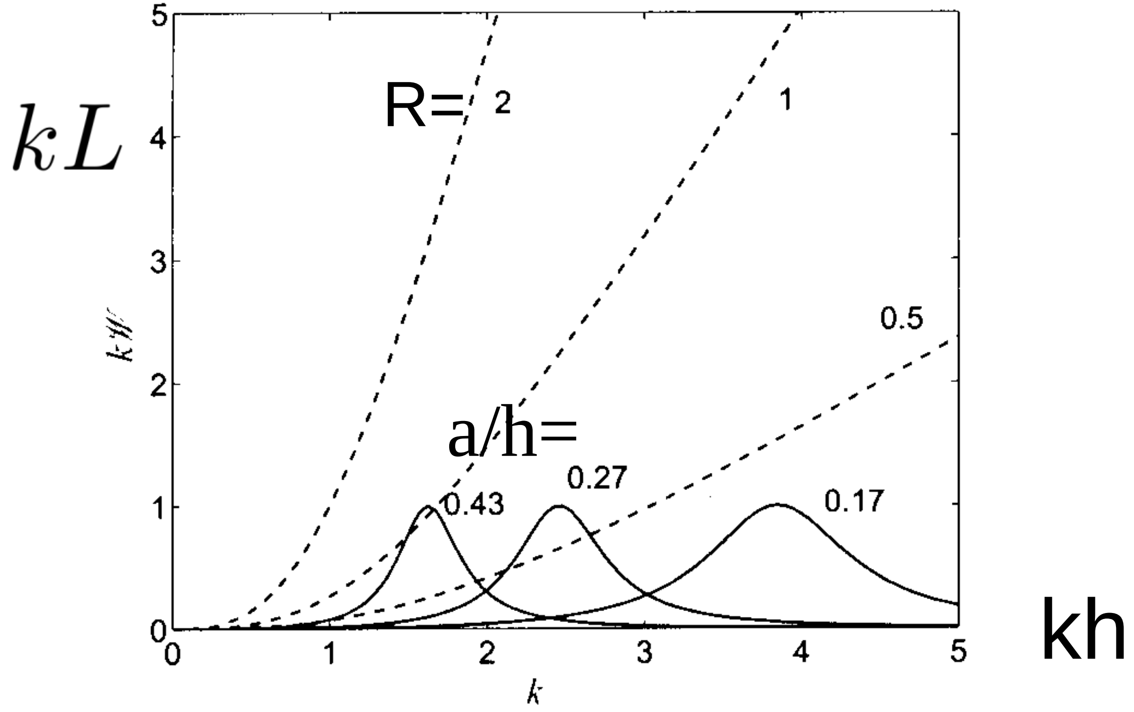


(c) $R = 5$



(d) $R = 5$

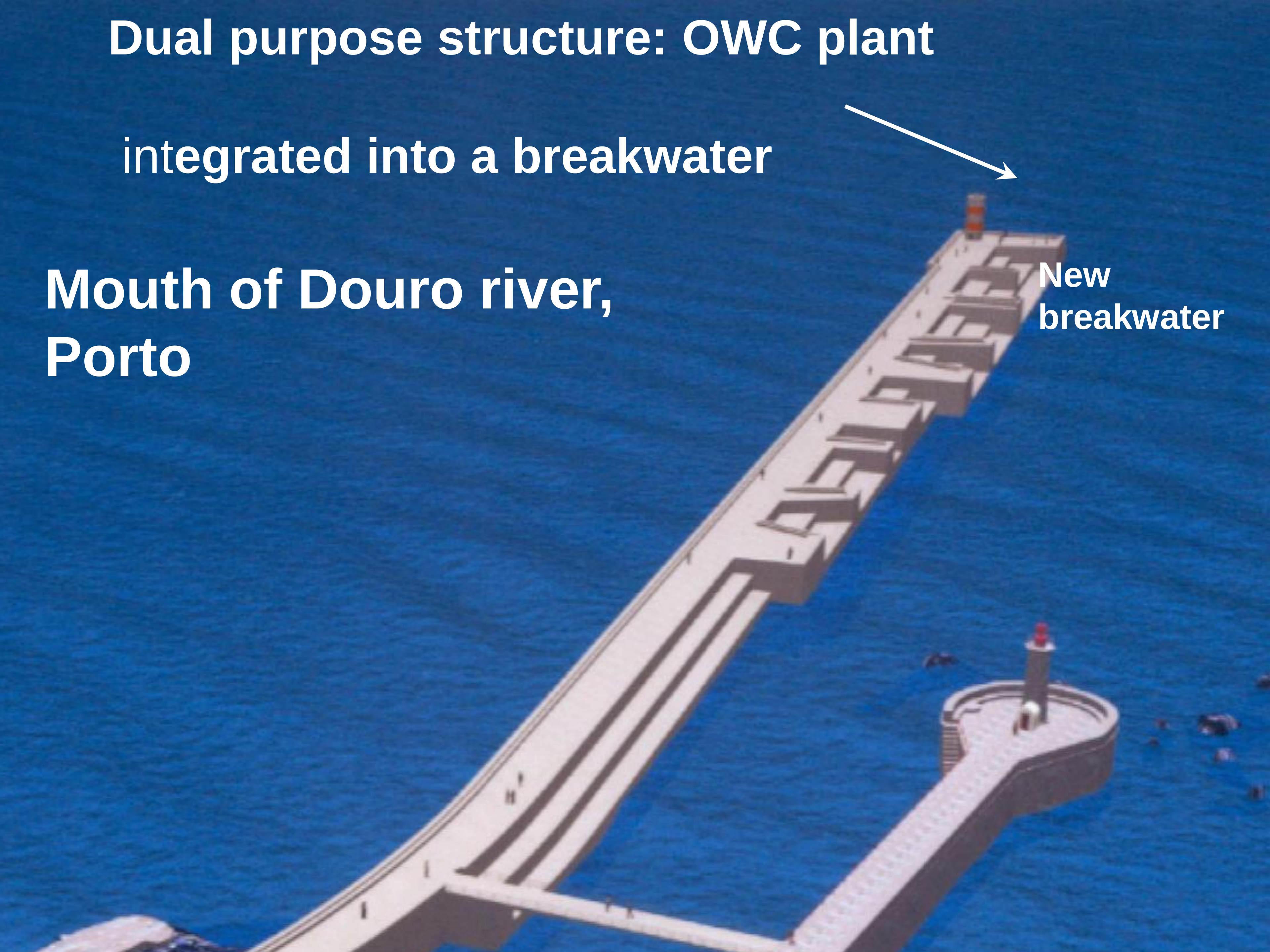
FO3 vs. single buoy of equal volume. f=0.2, λ_g=0.5



Array of compact arrays?

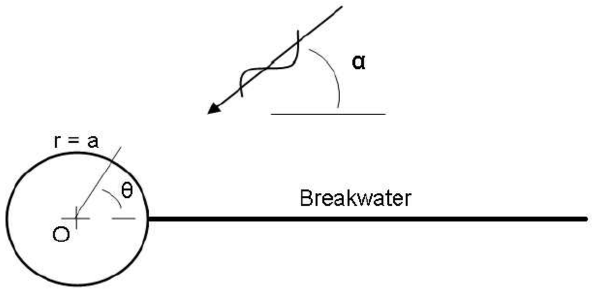
Dual purpose structure: OWC plant integrated into a breakwater

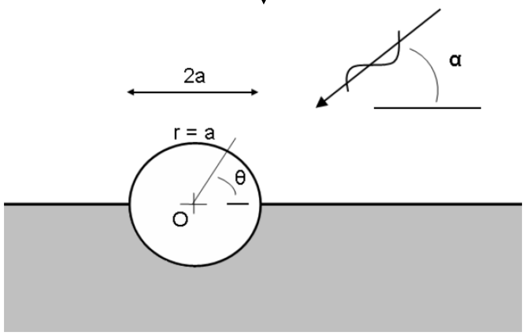
Mouth of Douro river, Porto



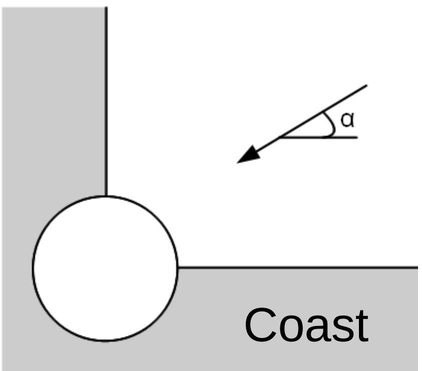
4 coastlines and OWC

Martin-Rivas & Mei (2008)

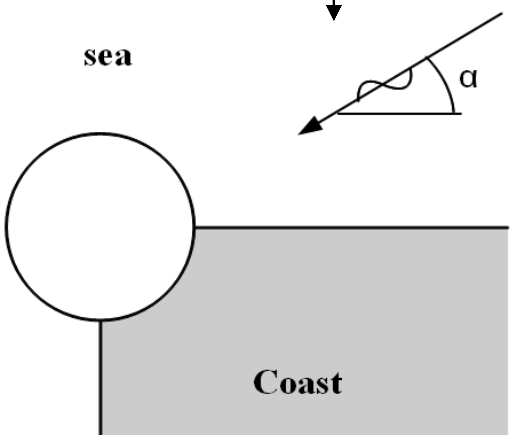




Lovas & Mei (2009)



Concave corner



Convex corner

Strategy of solution

Total solution=

Radiation due to uniform surface pressure

+ Diffraction (by solid cylinder and breakwater

+ correction for opening)

+ Coupling with chamber air and turbine

Assumptions:

Radius not small compared to depth & wavelength

Uniform air pressure in chamber.

Air is compressible and isentropic.

Maximum efficiency for one frequency?

$$kL = \frac{gka}{\omega C_g} \frac{\chi |\Gamma|^2}{(\chi + \tilde{B})^2 + (\tilde{C} + \beta)^2}$$

Sarmento & Falcao (1984)

(i) $$\text{If} \;\; \chi = \frac{\rho_w \omega K D}{a N \rho_a^0} = \tilde{B}(kh),$$

$$\text{Turbine absorption} = \text{radiation damping;}$$

(ii) $$\tilde{C}(kh) = -\beta = \frac{\omega^2 V_0 \rho_w}{c^2 a \rho_a}$$

$$\text{Restoring force} + \;\text{Effecive inertia} = \text{air elasticity}$$

$$\text{Theoretical optimum} : (kL)_{opt} = 1$$

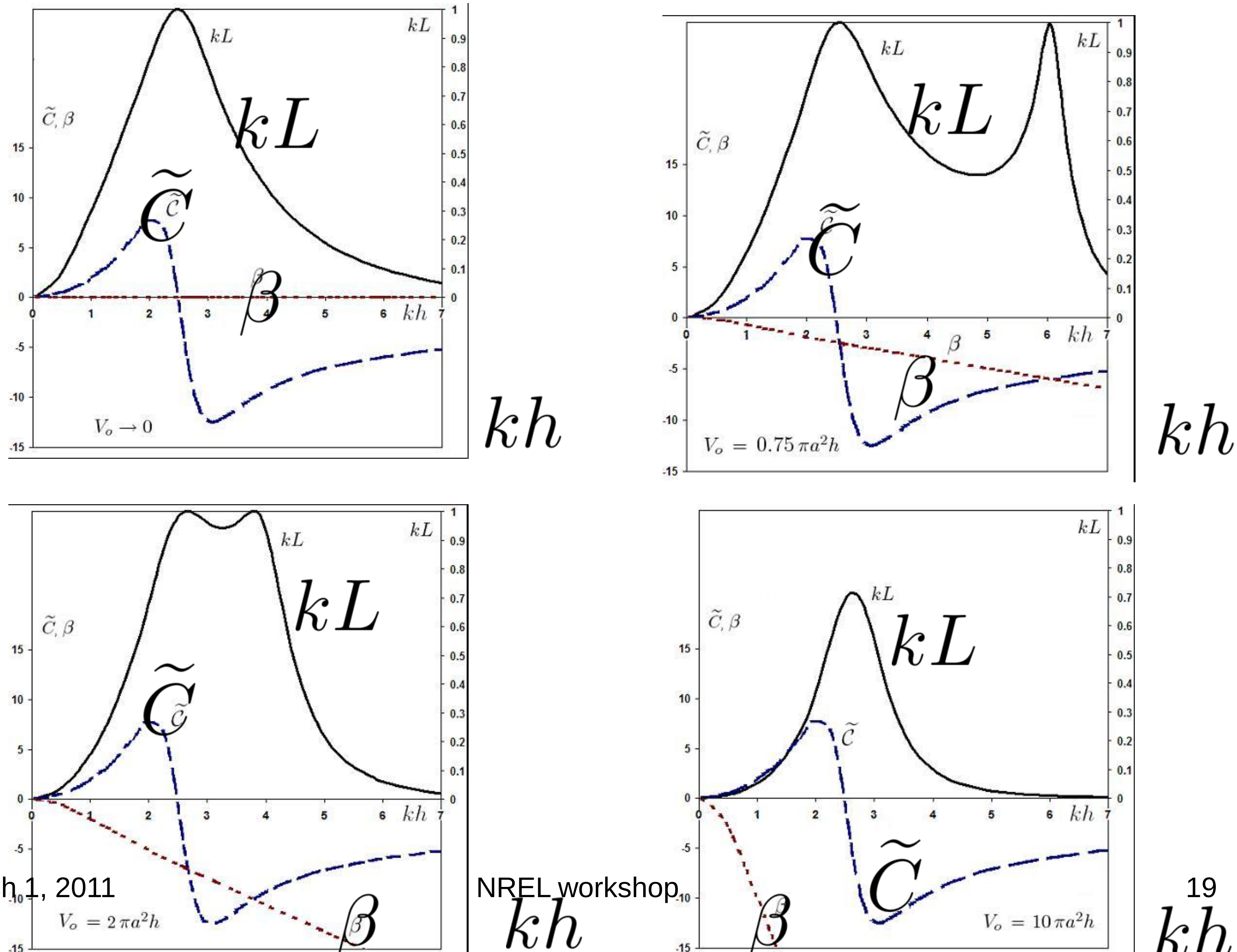
Optimization for all frequencies by proper design of turbine system alone

$$\frac{\partial(kL)}{\partial\chi} = 0$$

$$\chi_{opt}(\omega) = \sqrt{B^2 + (C+\beta)^2}$$

$$\beta = -\frac{\omega V_0}{c^2 \rho_0^2}, \qquad V_0 = \text{fixed}$$

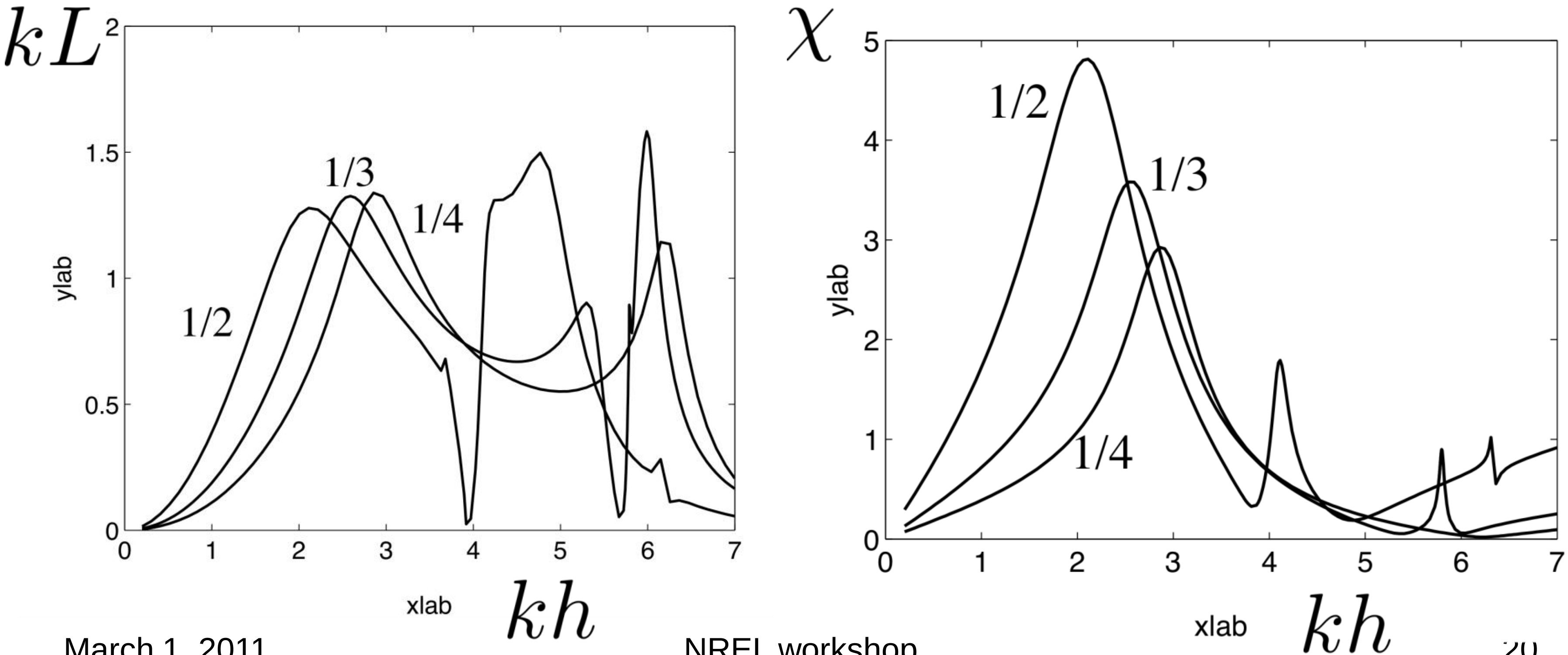
Fixed OWC radius, different chamber height (volume)



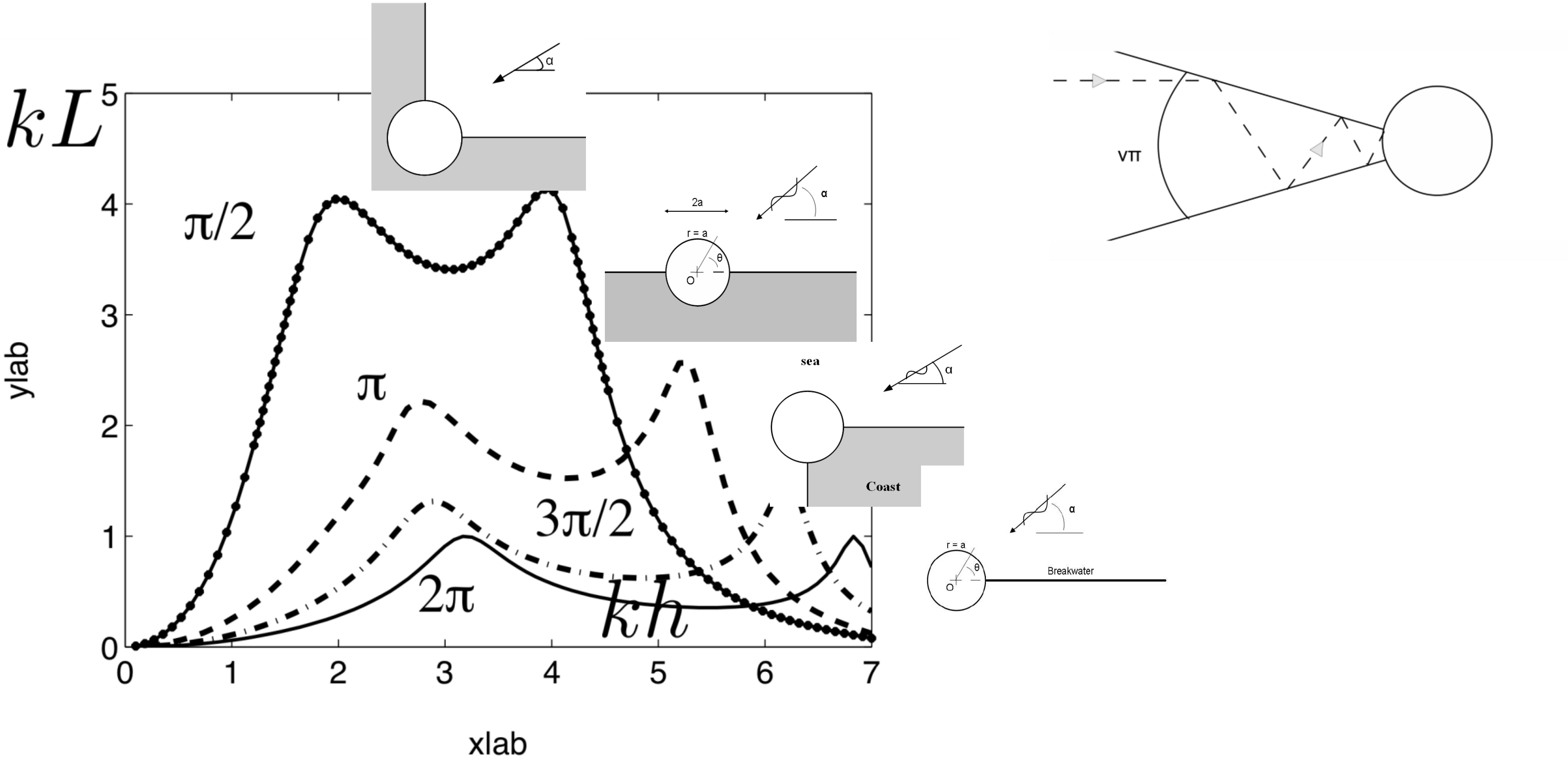
IDEAL OPTIMIZATION FOR ALL FREQUENCIES

Fixed chamber volume, $V_0 = \pi a^2 h$

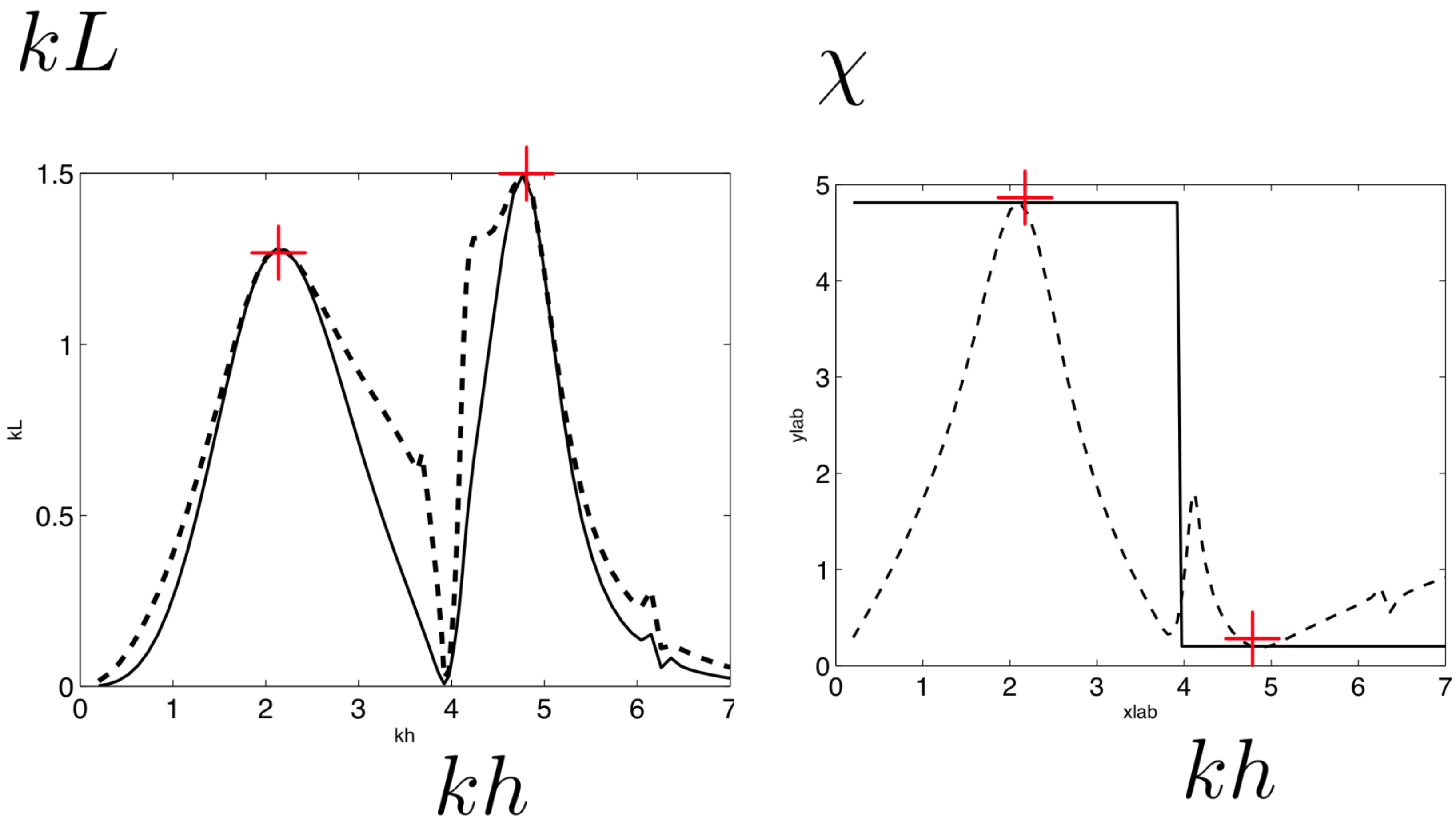
$a/h = 1/2.1/3, 1/4$



Comparison of 4 coastlines



Practical optimization



Conclusions

- Large OWC allows more modes, efficiency bandwidth increases
- Chamber can be selected to broaden bandwidth
- Practical turbine control can broaden bandwidth.
- Needed: Nonlinear modeling, Control of Power- takeoff