Webinars

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The program will begin soon.

You will not hear audio until we begin.

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Multiphase Flow Measurement Sensing Domains, Part 1: Electromagnetics

Robert Adams, Aramco Americas: Aramco Research Center – Houston

September 6th, 2022

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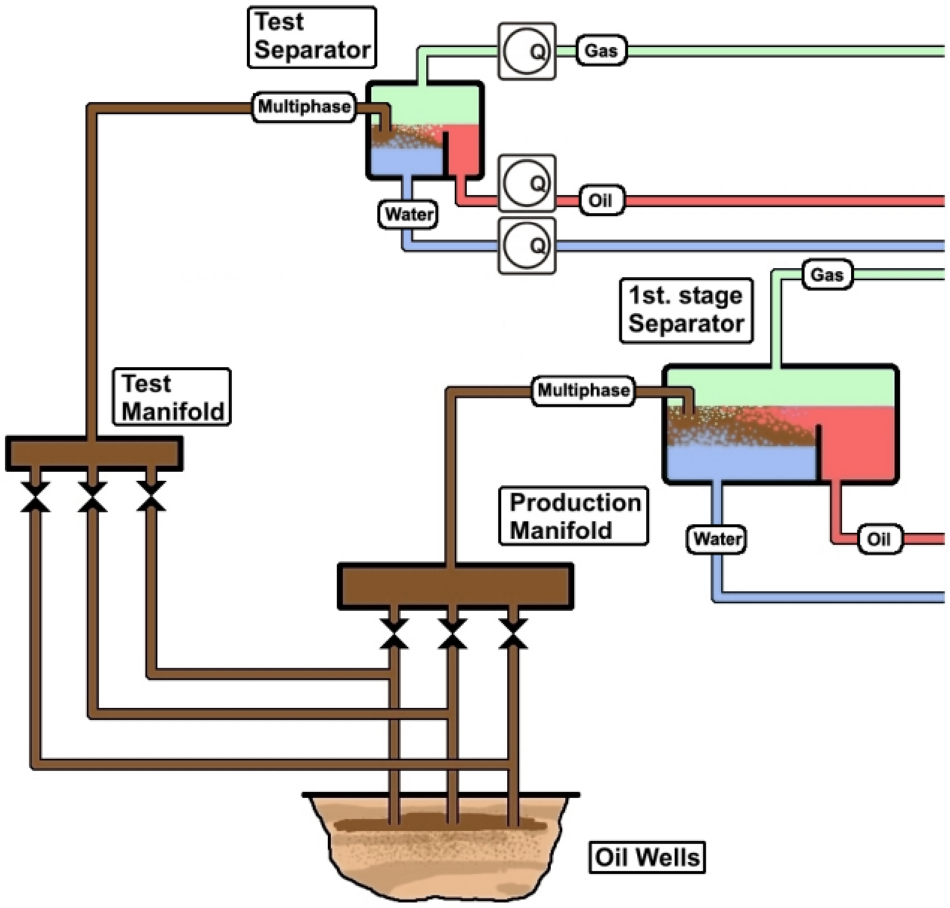
Agenda

1. Multiphase Flow Meters (MPFMs) for the Oil & Gas Industry
2. Sensing Domains Overview
3. Electromagnetic Sensing Domains
   i. Oil/Water/Gas Measurement Phenomena
   ii. Phase Fraction Measurement Techniques
   iii. Flow Rate Measurement Techniques
   iv. Flow Regime Dependence
4. Conclusions & Acknowledgements

Multiphase Flow Background

- Multiphase Flow Meters (MPFMs)
  - Continuous measurements of oil/water/gas flow rates
  - Replace test separators
  - Increase production optimization & allocation
  - Decrease OPEX & HSE risk



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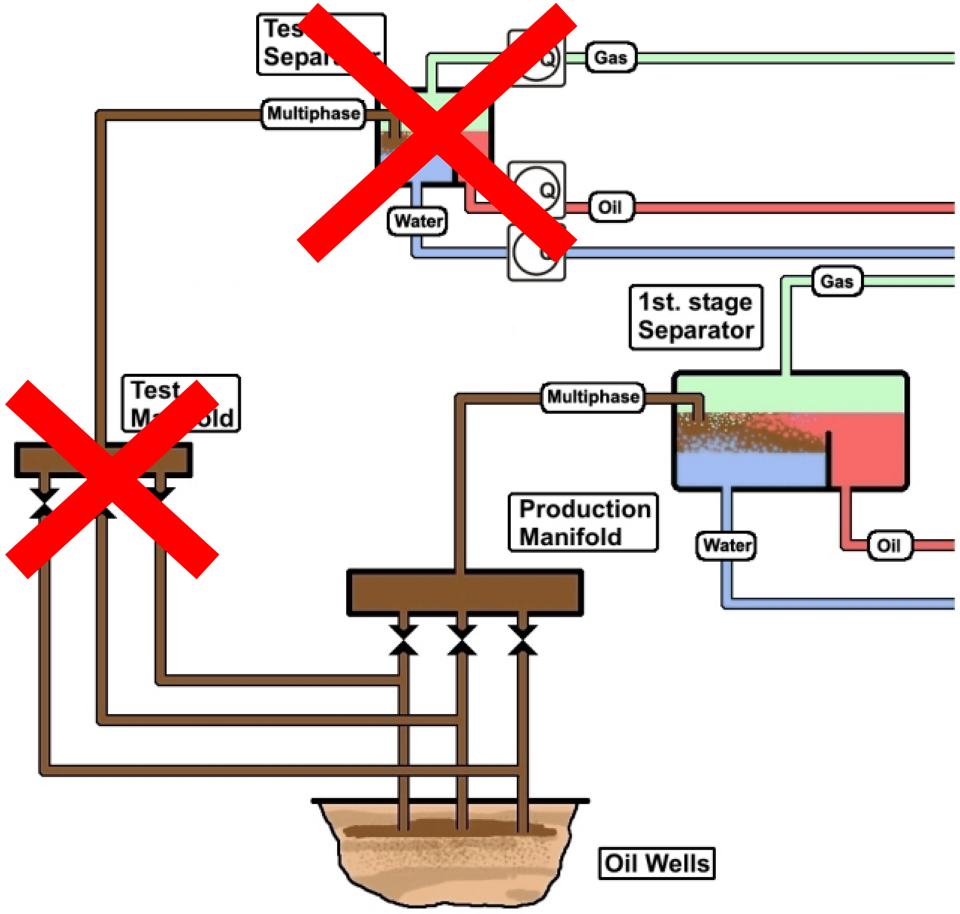

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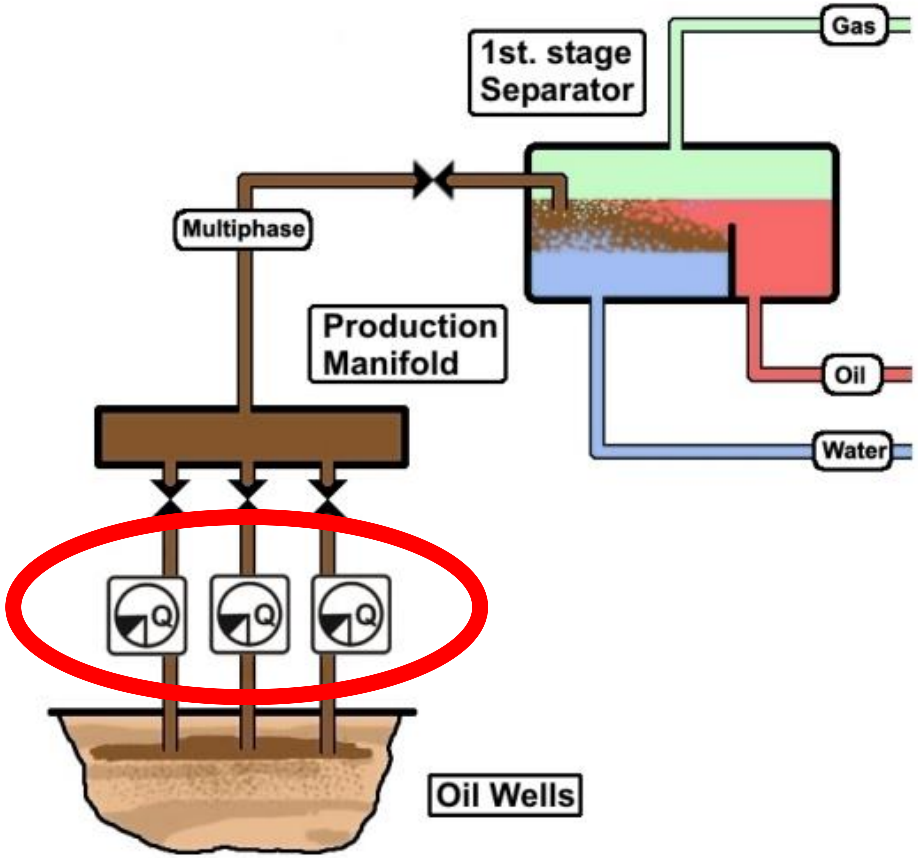

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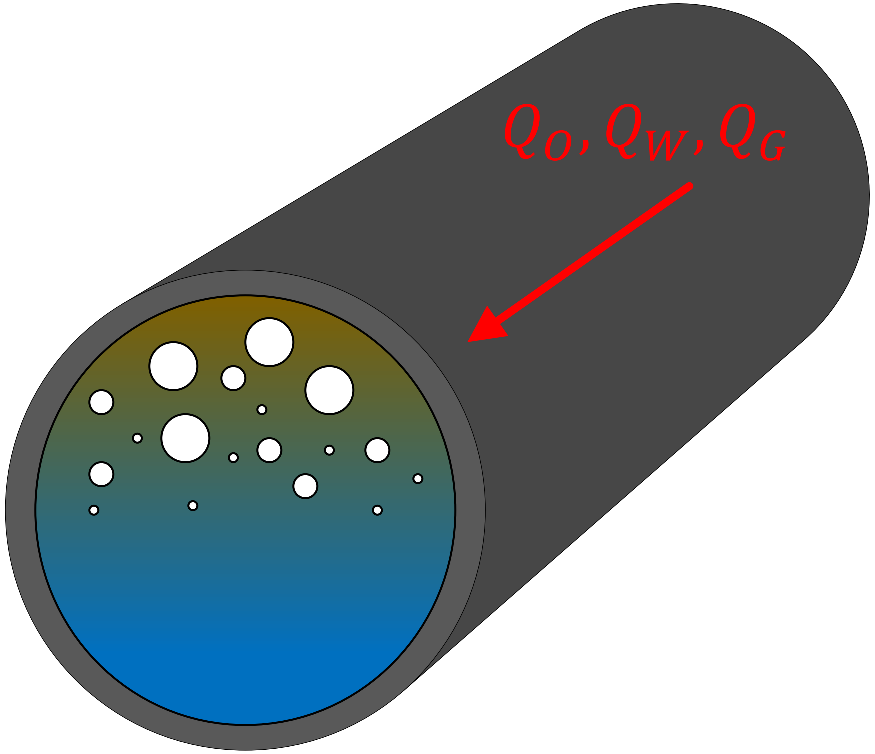
Multiphase Flow Background

- Flow rates of oil/water/gas
  - Three equations and three unknowns

$$Q_{TOT} = Q_O + Q_W + Q_G$$

$$S_1 = f_1(Q_O, Q_W, Q_G)$$

$$S_2 = f_2(Q_O, Q_W, Q_G)$$



Multiphase Flow Background

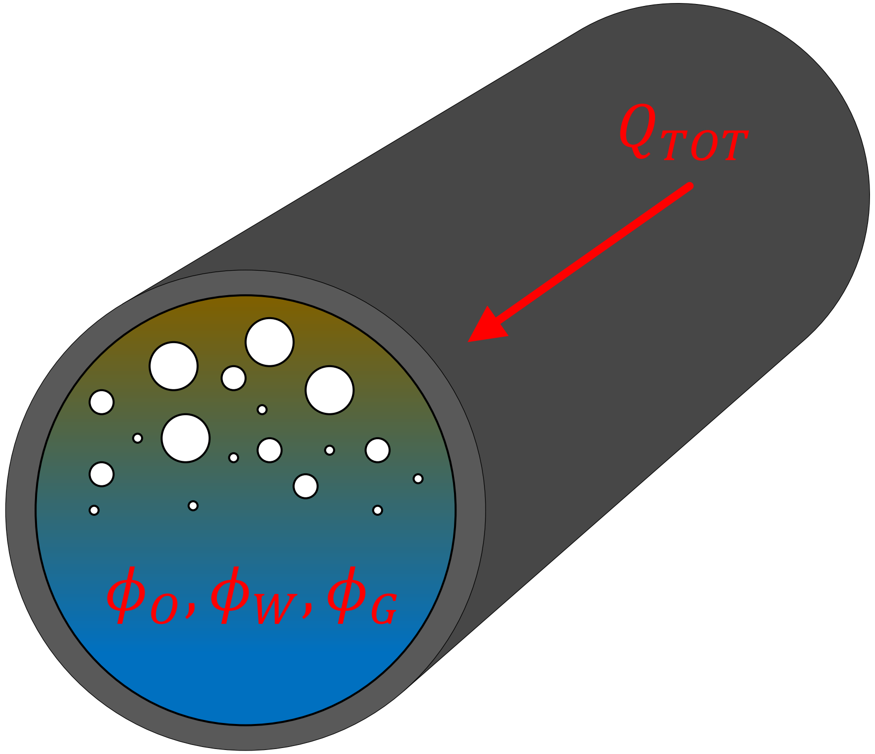
- Phase fractions of oil/water/gas and total flow rate
  - Four equations and four unknowns
  - Assumes no slip between phases

$$1 = \phi_O + \phi_W + \phi_G$$

$$S_1 = f_1(\phi_O, \phi_W, \phi_G)$$

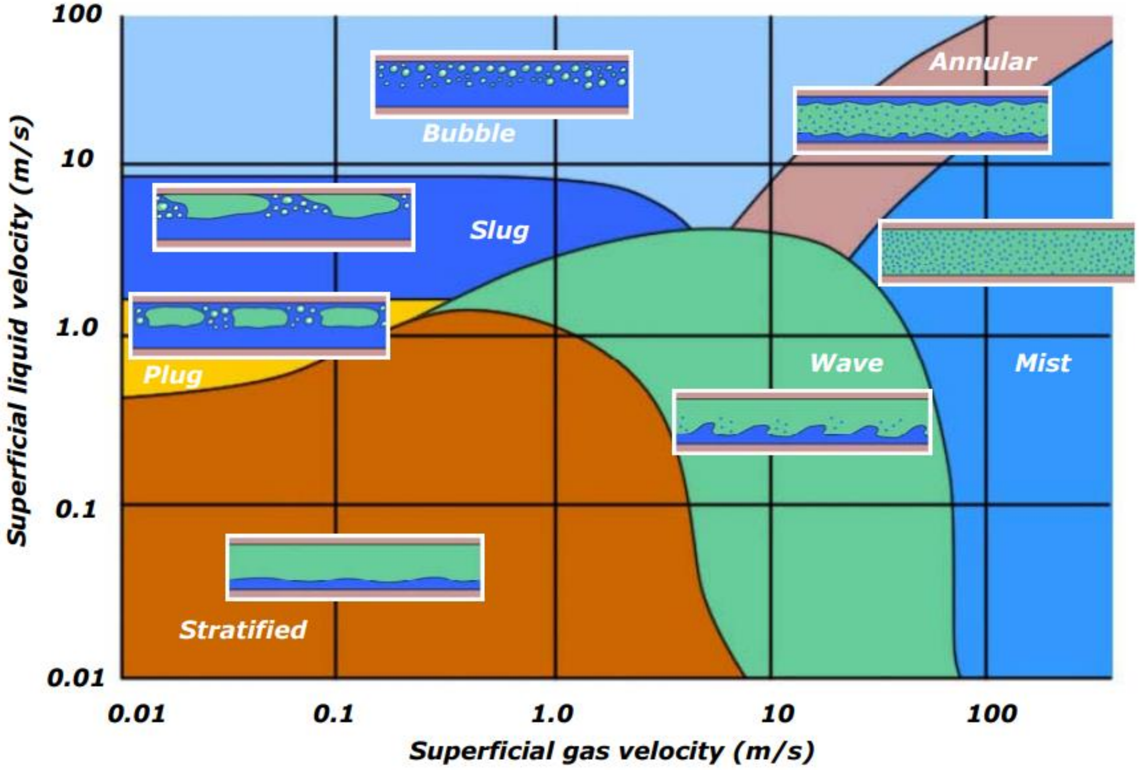
$$S_2 = f_2(\phi_O, \phi_W, \phi_G)$$

$$Q_{TOT} = Q_{TOT} \cdot \phi_O + Q_{TOT} \cdot \phi_W + Q_{TOT} \cdot \phi_G$$

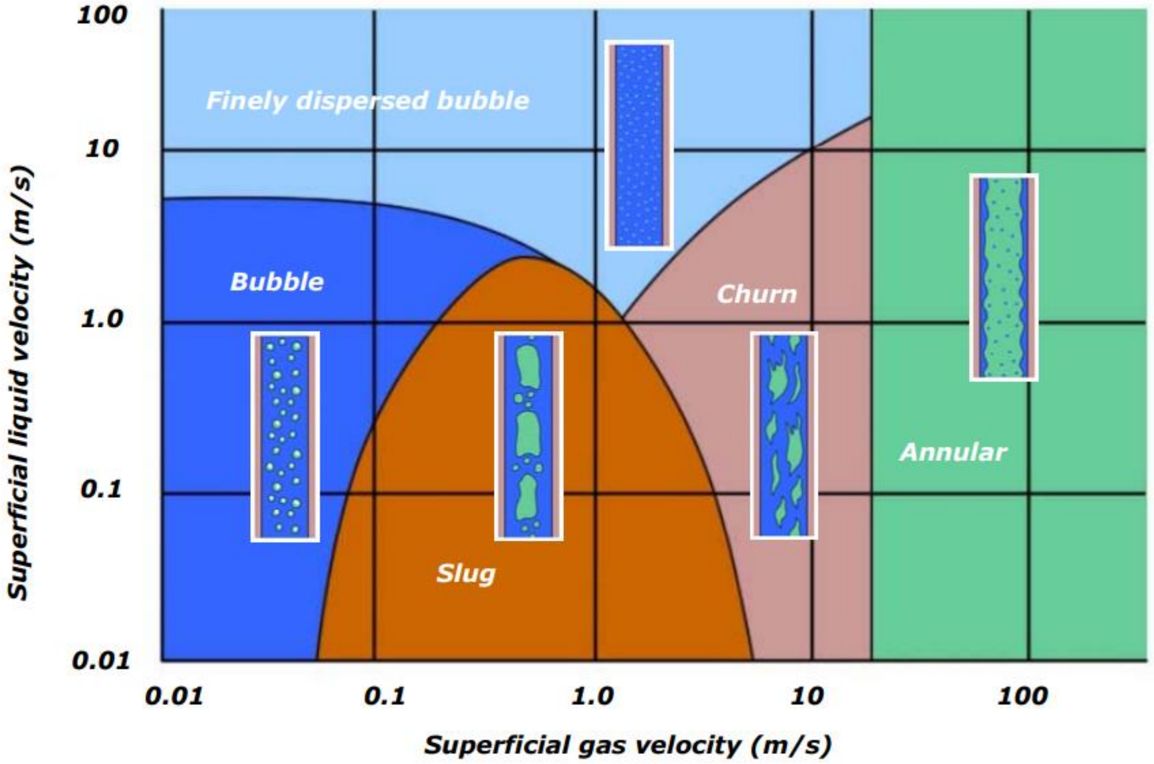


Multiphase Flow Background

Horizontal Flow Regimes



Vertical Flow Regimes



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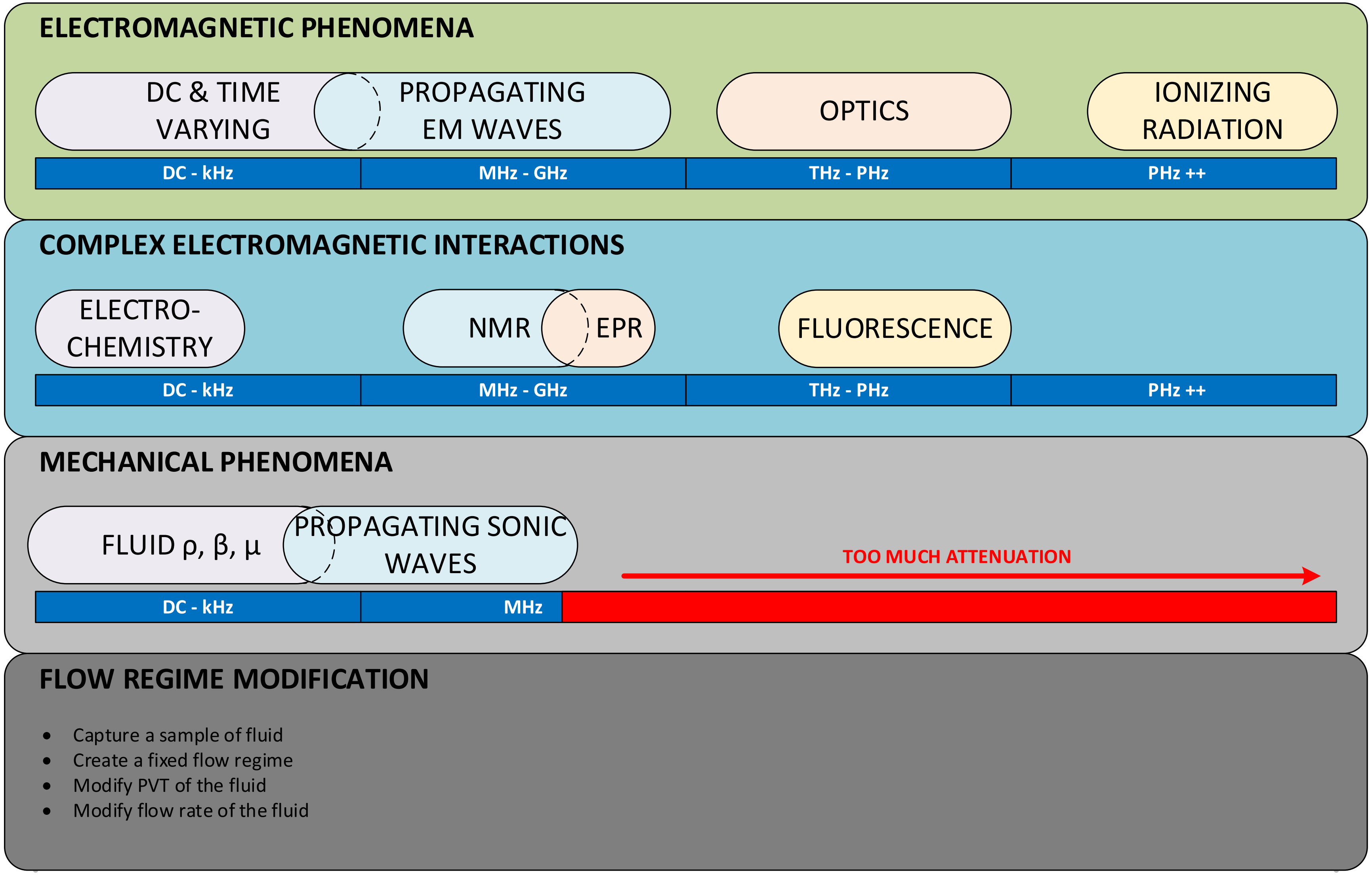
Multiphase Flow Sensing Domains



Overview of Electromagnetic Sensing

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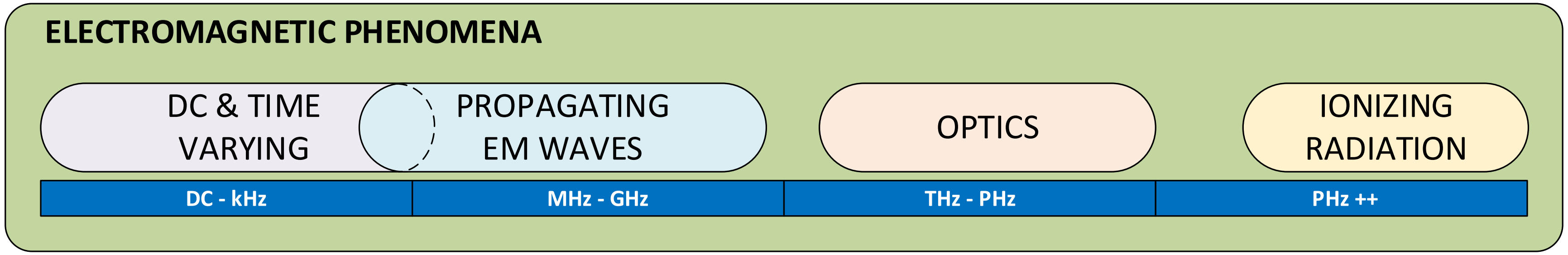
- Part 1 will focus on Electromagnetic (EM) phenomena
- Progress thru the electromagnetic spectrum from low frequency to high frequency
- Measurement examples from each EM domain that can be used in MPFM systems to discriminate phase fractions and flow rates



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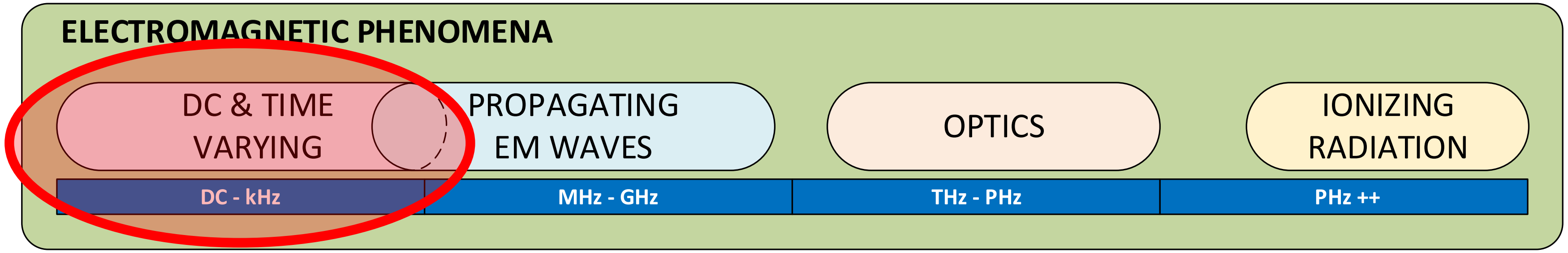


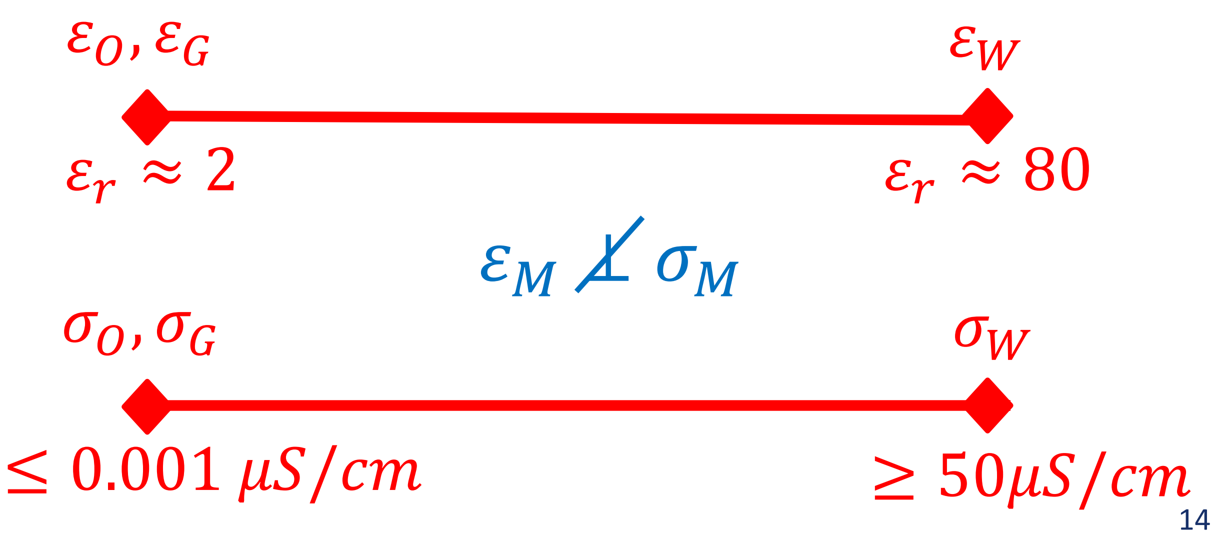
DC & Time Varying Electromagnetics

- In this frequency range, quantify fluid phases with conductivity (σ) and permittivity (ε)
- Difficult to discriminate oil and gas, typically provide just watercut
- Changes in σ and ε for oil/water/gas are NOT independent

$$1 = \phi_W + \phi_{O+G}$$

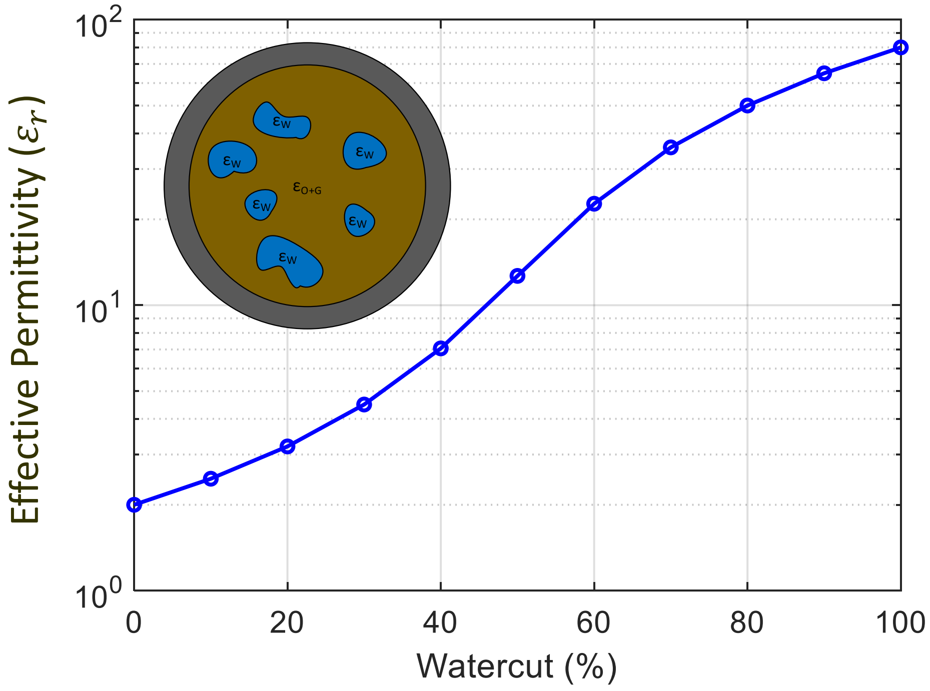
$$\varepsilon_M = f(\phi_W, \phi_{O+G})$$

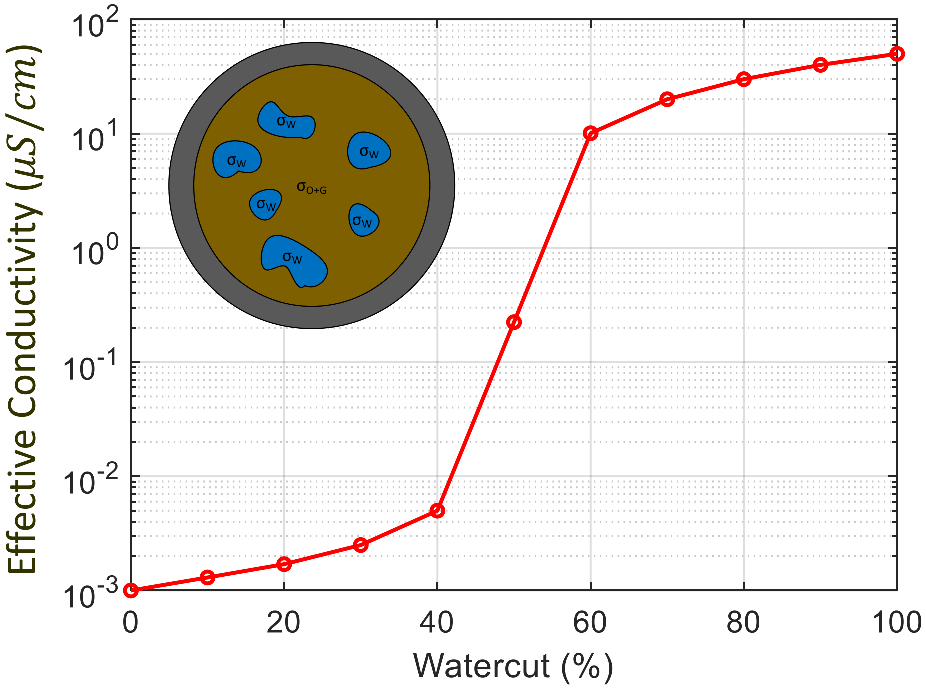
$$\sigma_M = f(\phi_W, \phi_{O+G})$$



DC & Time Varying Electromagnetics

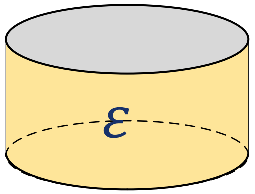
- Arbitrary distributions of σ and ε, depending on fluid mix and flow regime
- Effective medium theory: mixing laws for homogeneous fluid mixtures
  - Landaur, Bruggemann, Maxwell-Garnett, etc.



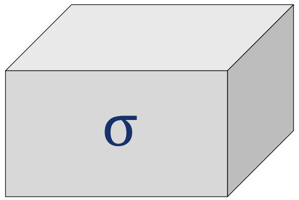


DC & Time Varying Electromagnetics

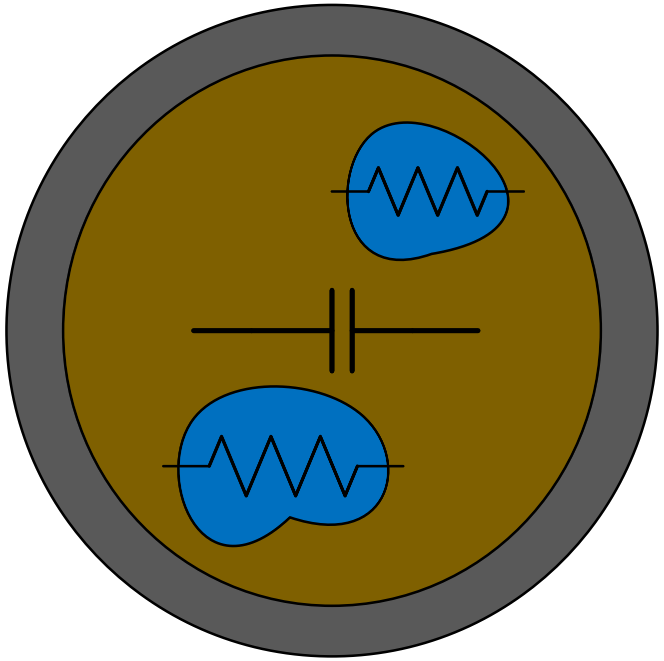
- In this domain, quantify σ and ε of fluid mixtures by measuring the impedance distribution of the multiphase fluid mix
- Fluid mixtures as distributed resistors (1/σ) and capacitors (ε)



$$C \sim \varepsilon$$

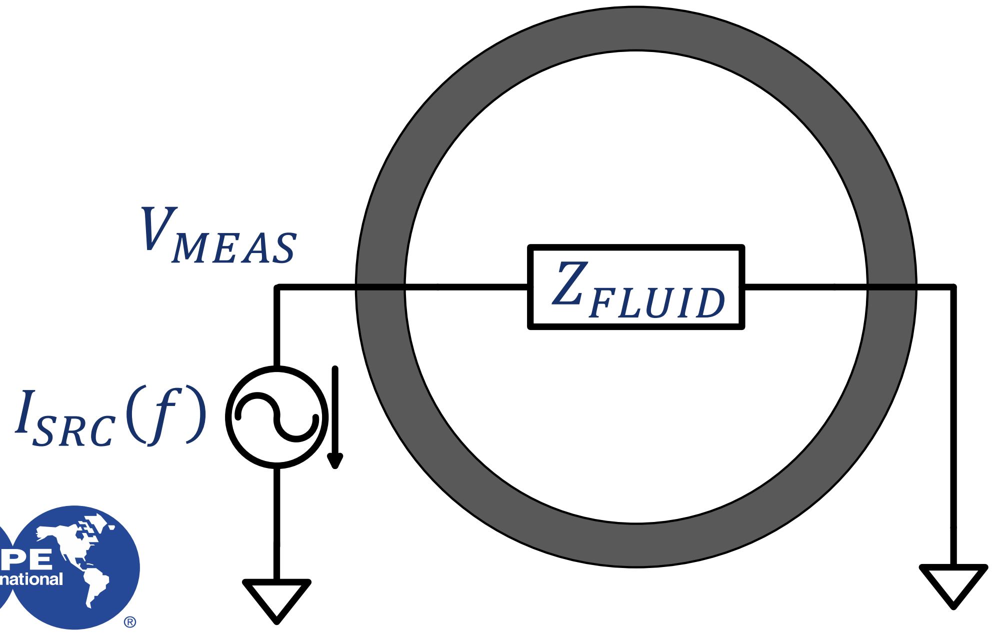


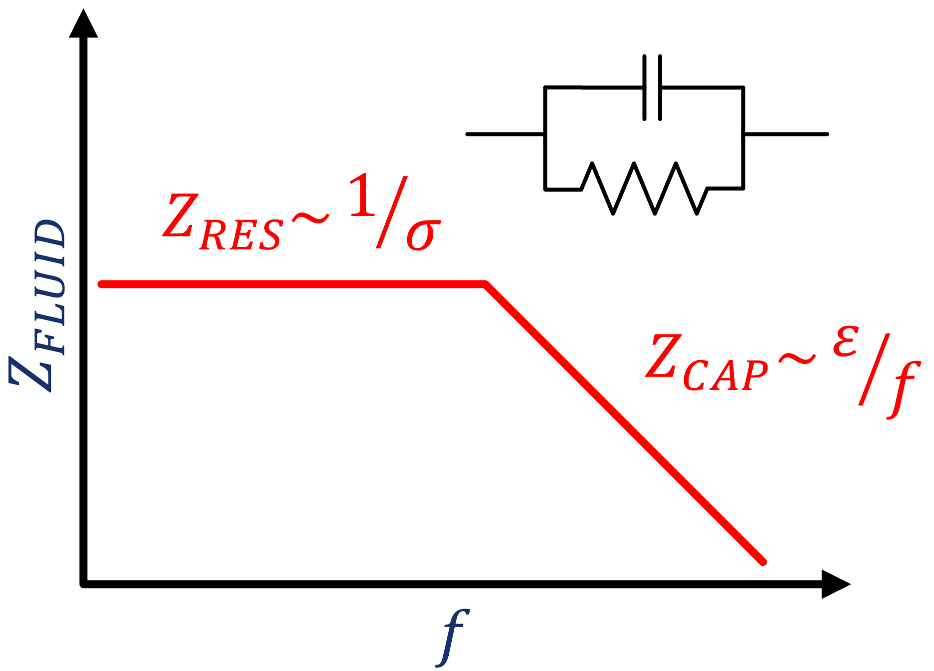
$$R \sim {}^{1}/_{\sigma}$$



DC & Time Varying Electromagnetics

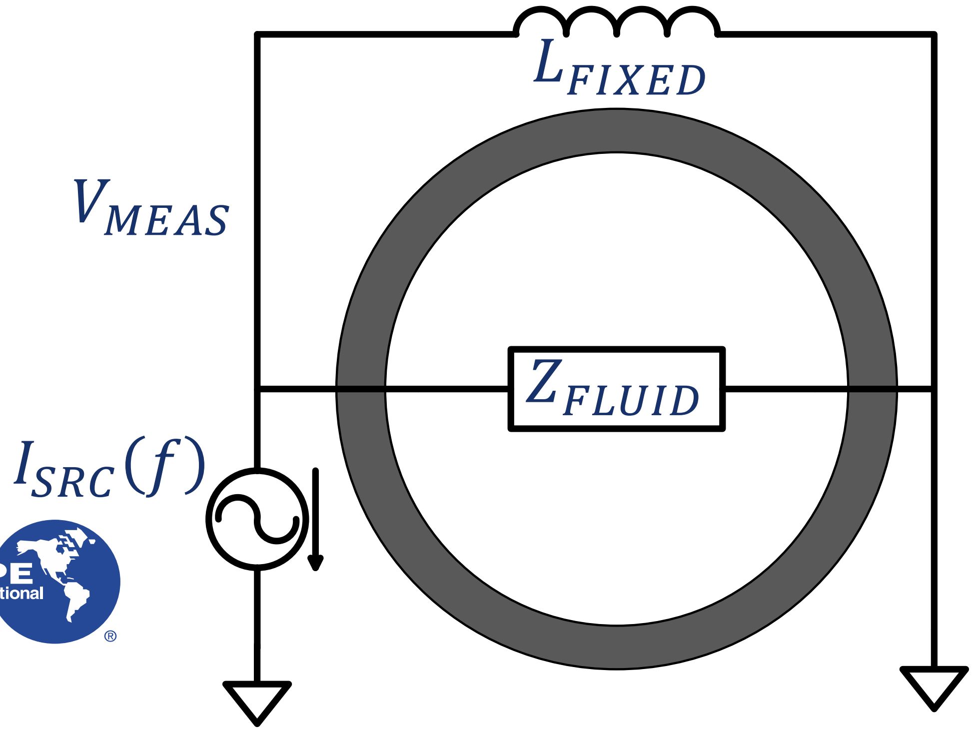
- Measure impedance of fluid in broad frequency range
  - Assume some distribution of capacitors & resistors (flow regime)
  - Extract σ and ε from impedance vs. frequency plot behavior

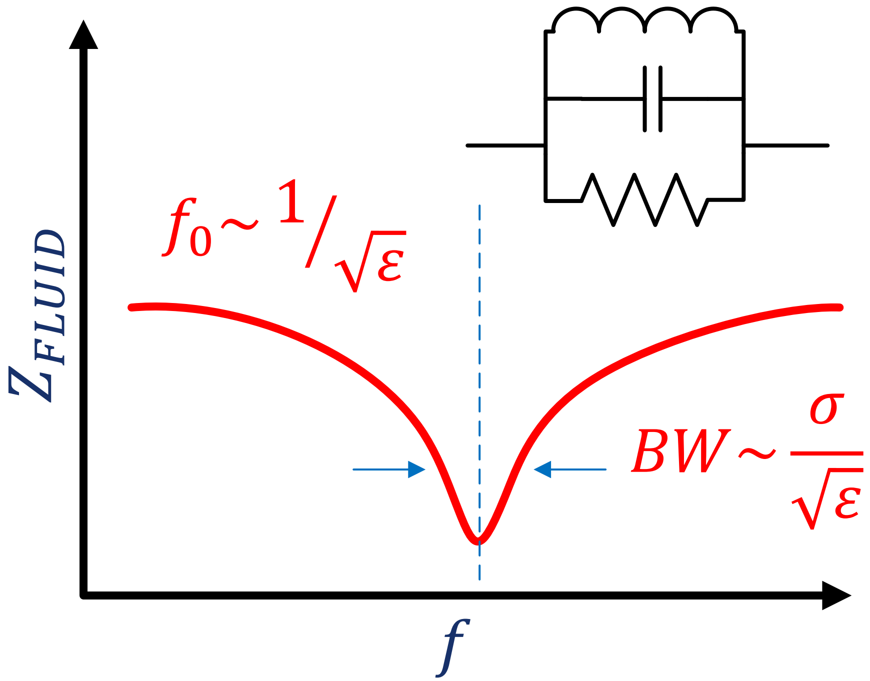




DC & Time Varying Electromagnetics

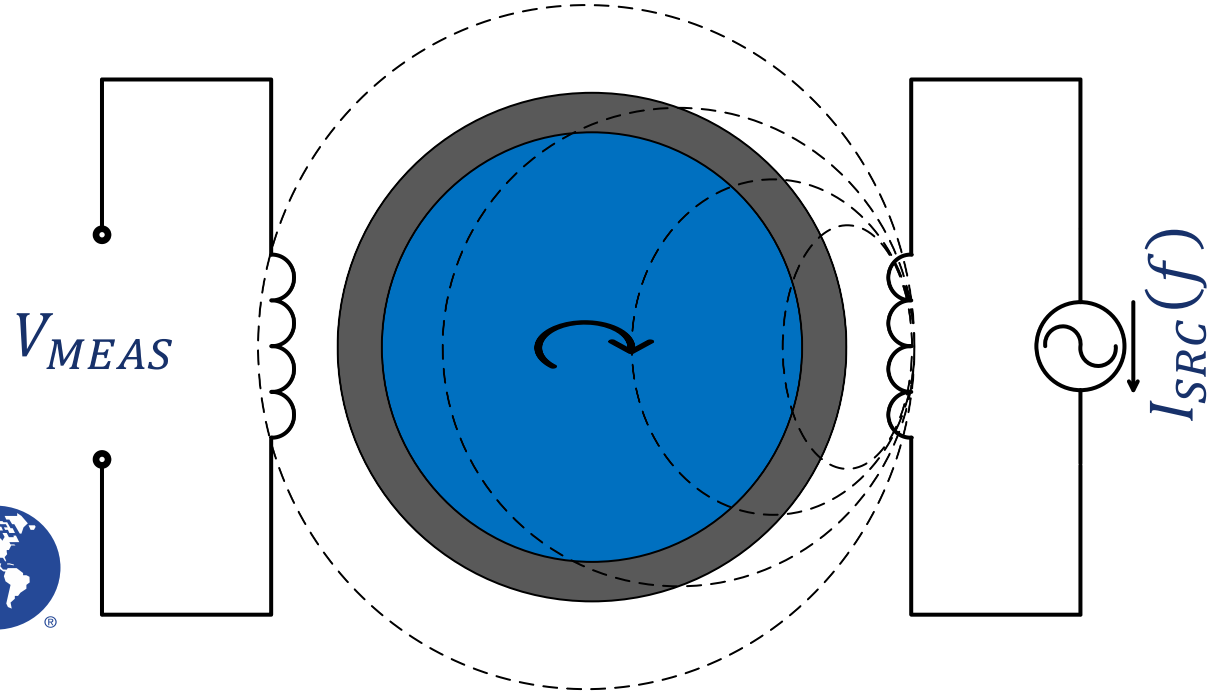
- Measure impedance of fluid around resonant frequency
  - Assume some distribution of capacitors & resistors (flow regime)
  - Extract σ and ε from impedance vs. frequency plot behavior





DC & Time Varying Electromagnetics

- Eddy current generation in conductive media to quantify σ
  - Modify mutual inductance due to opposing magnetic field
  - Skin depth vs. frequency to target different sizes of conductive media



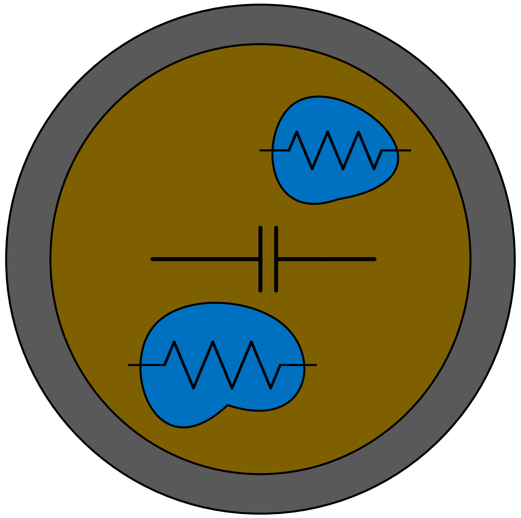
$V_{MEAS} \sim f M I_{SRC}$

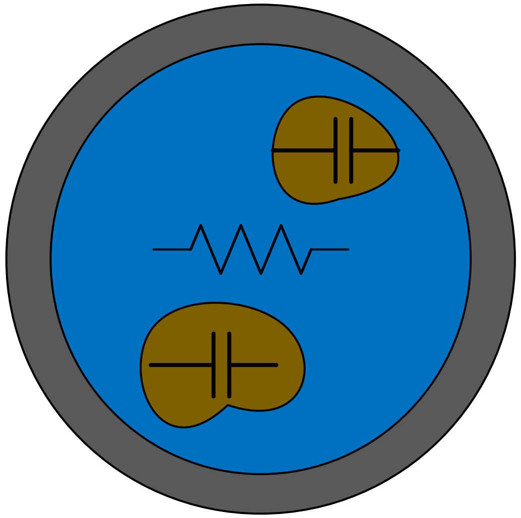
$\sigma \uparrow, M \downarrow$

$\delta \sim \frac{1}{\sqrt{f\sigma}}$

DC & Time Varying Electromagnetics

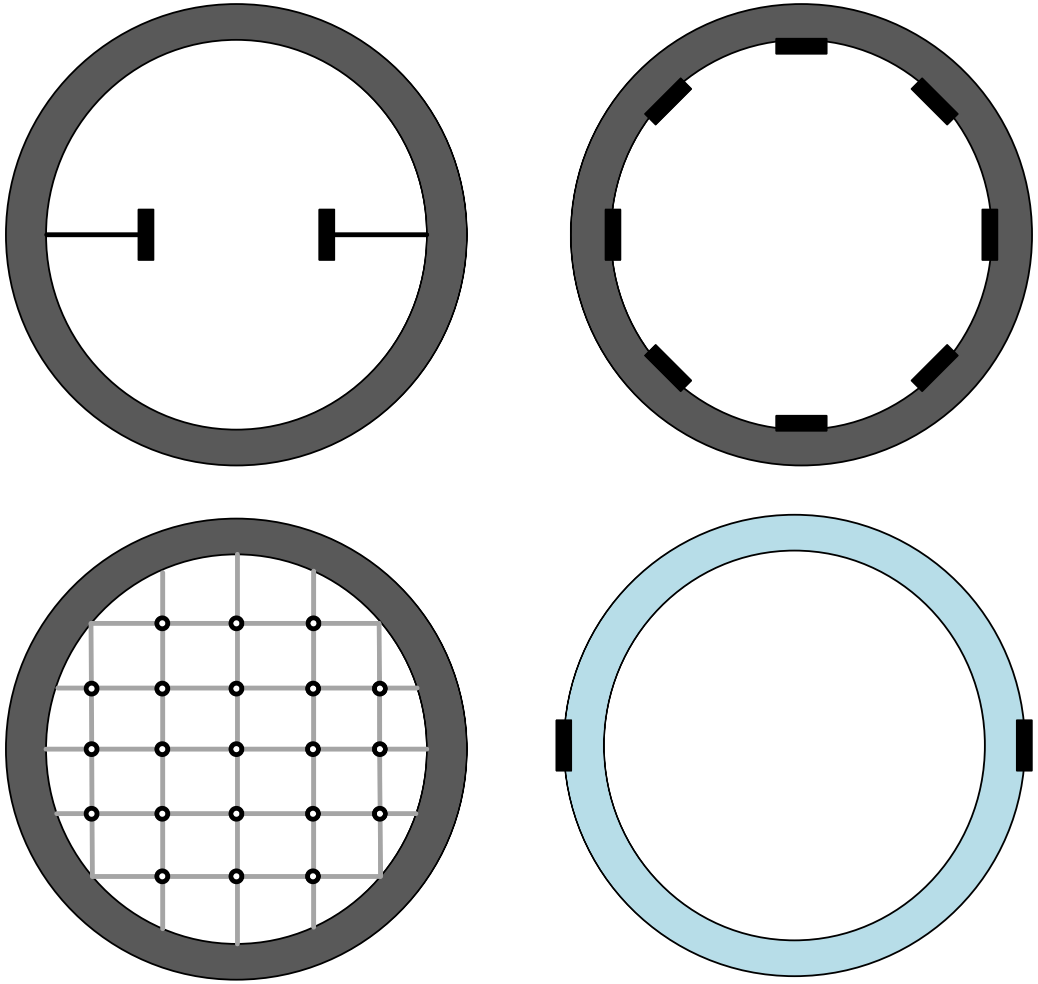
- Phase inversion region: transition from oil continuous to water continuous and vice versa
  - Resistance of conductive media blocked by non-conductive path
  - Capacitance of dielectric media shorted out by conductive path





DC & Time Varying Electromagnetics

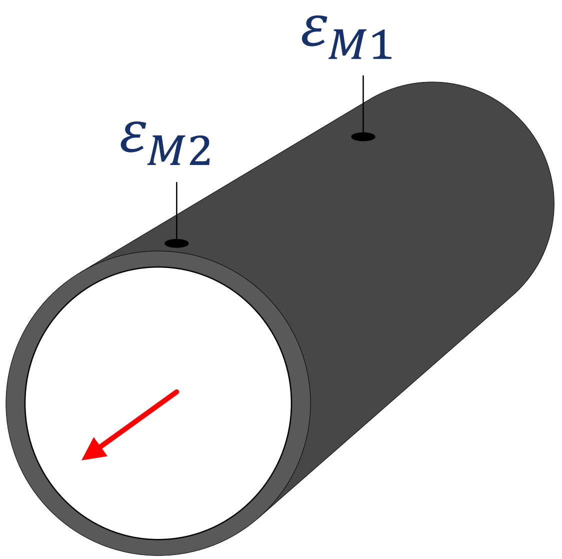
- Internal EM probes:
  - Point sampling
  - Electrode arrays on circumference
  - Grid within pipe
  - Tomographic imaging
- External EM probes:
  - Metal pipe shorts out response
  - Some methods made thru non-conductive pipe

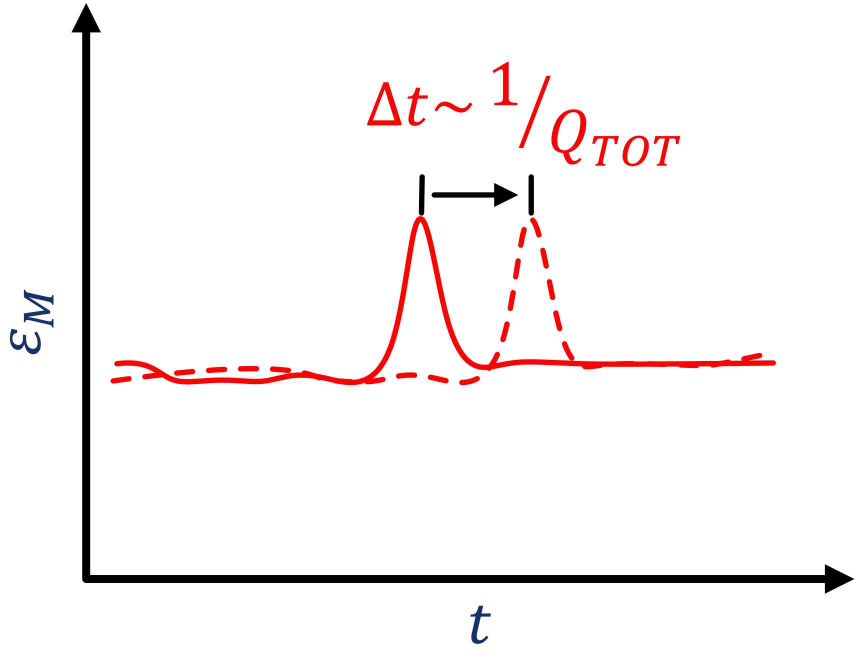


DC & Time Varying Electromagnetics

- Flow rate estimation with cross correlation

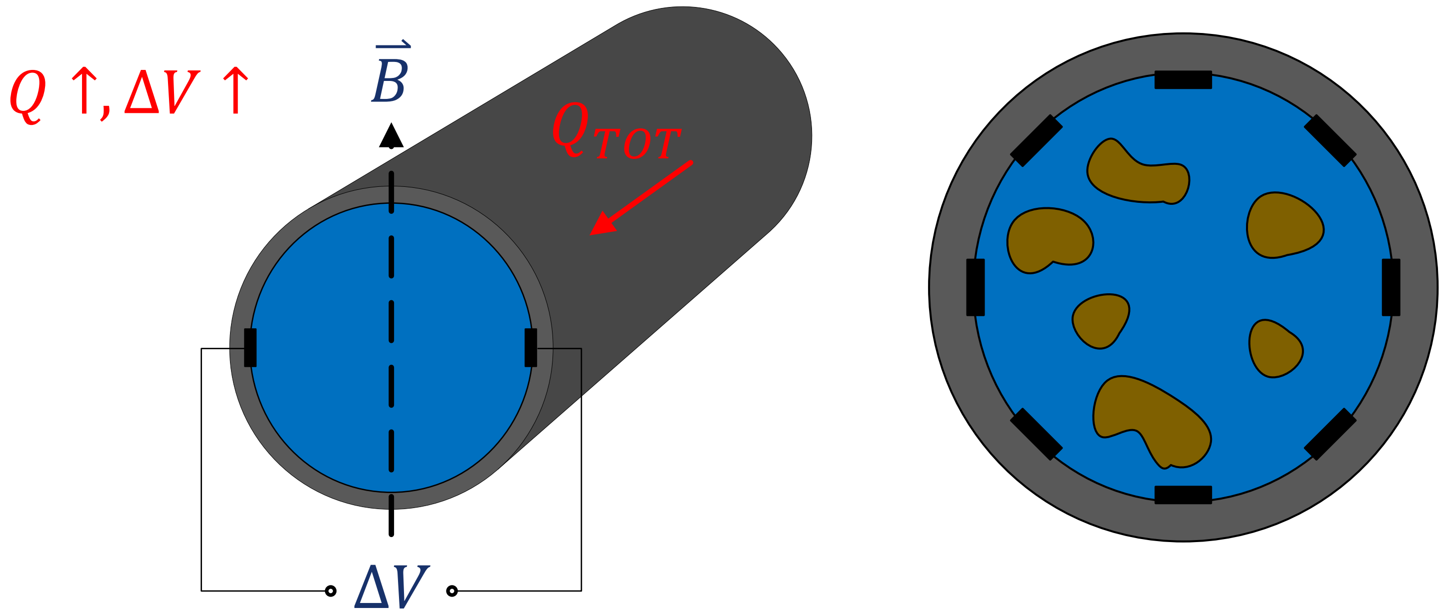
$$Q_{TOT} = Q_{TOT} \cdot \phi_O + Q_{TOT} \cdot \phi_W + Q_{TOT} \cdot \phi_G$$





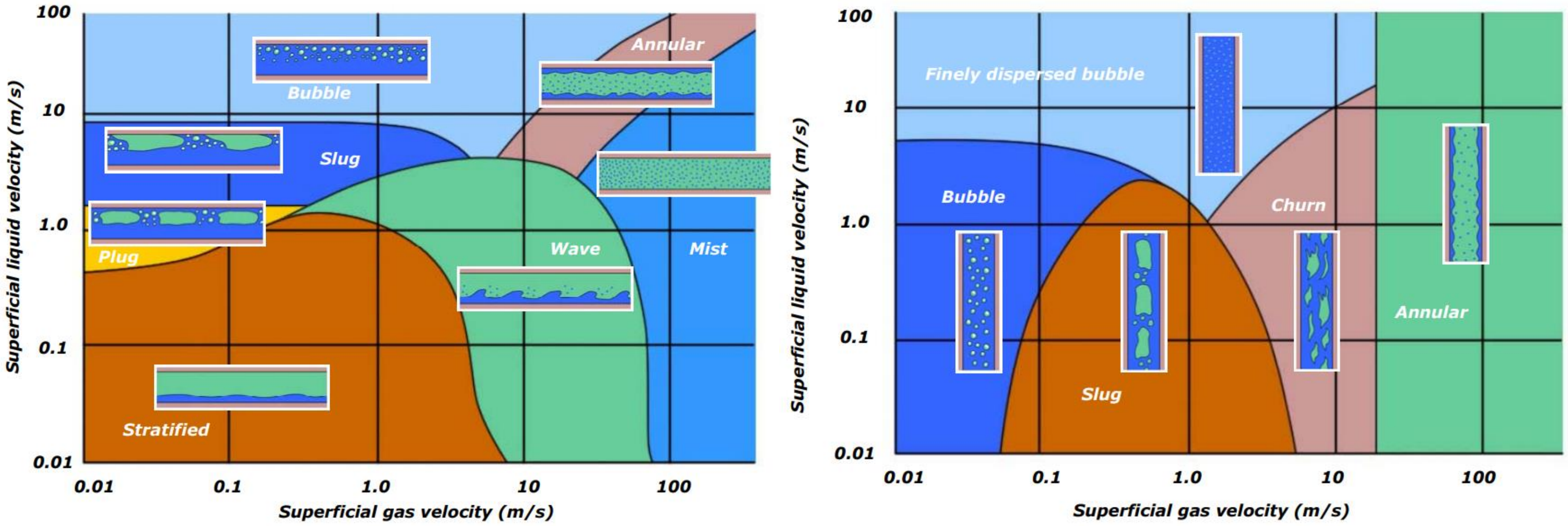
DC & Time Varying Electromagnetics

- Flow rate estimation with Faraday's Law
  - More complex with multiple phases / different geometries.
  - Requires water phase continuity between electrodes



DC & Time Varying Electromagnetics

- Measurements are flow regime dependent, so well defined and/or homogeneous flows
- Phase inversion region leads to model breakdown & inaccuracy



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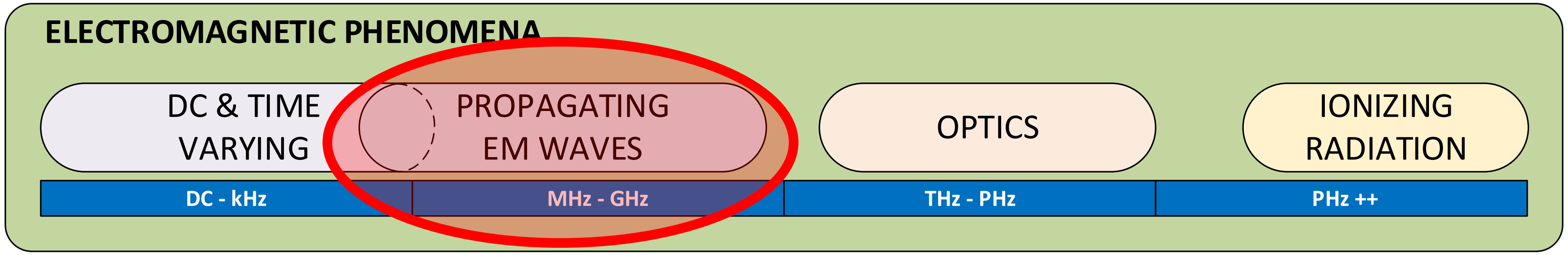
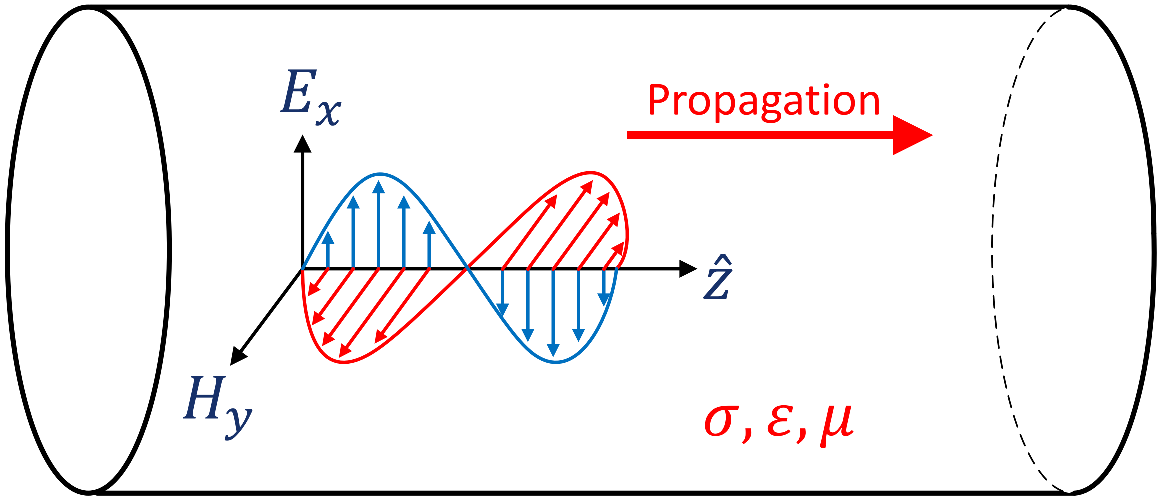
Overview of Electromagnetic Sensing

- Propagating EM waves
  - Stationary charge (electrostatics) to moving charge (electrodynamics)
  - Frequency range spans $\sim 100MHz$ to $\sim 100GHz$



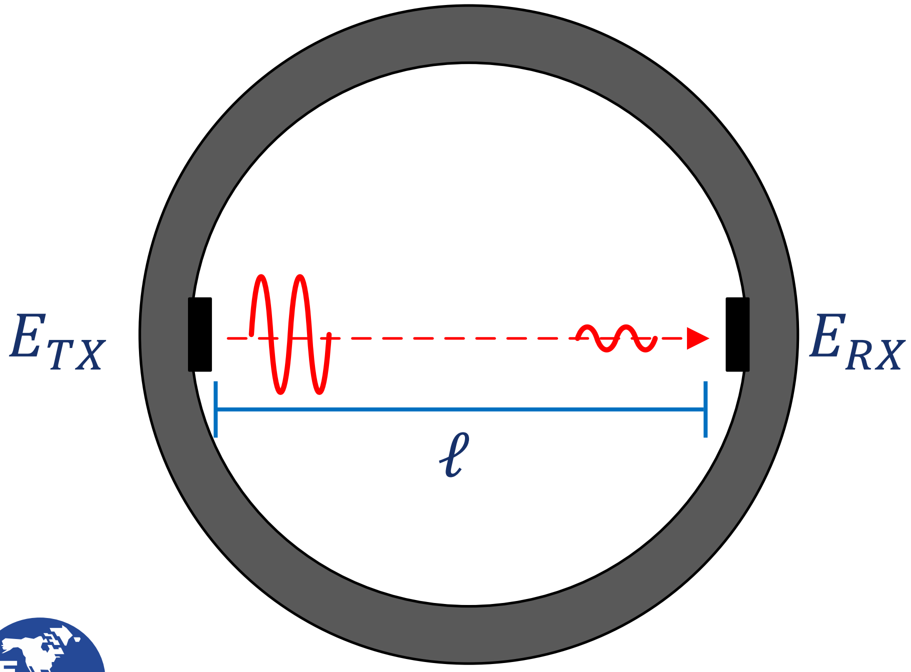
Propagating Wave Electromagnetics

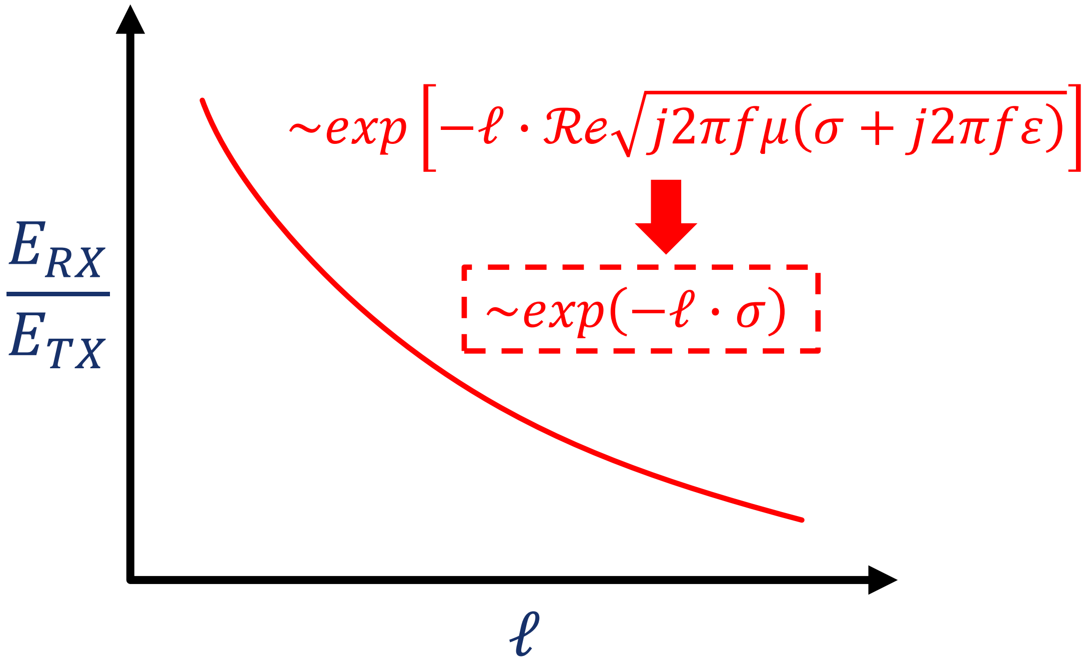
- In this frequency range, EM waves propagate through the fluid
  - Take advantage of different physics to measure fluid properties
  - Phase fractions are still quantified by electromagnetic properties σ and ε
  - Same fundamental issue with differentiating water vs. oil/gas, and no independence between σ and ε functions, e.g. $\phi_W + \phi_{O+G}$



Propagating Wave Electromagnetics

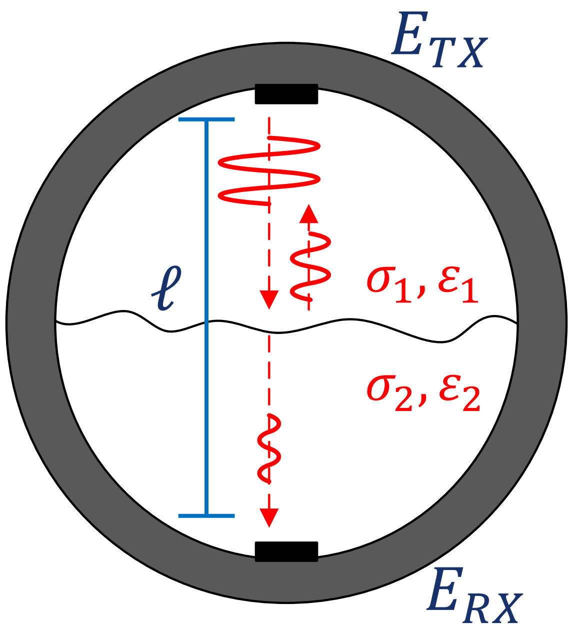
- Quantify σ via attenuation of propagating wave

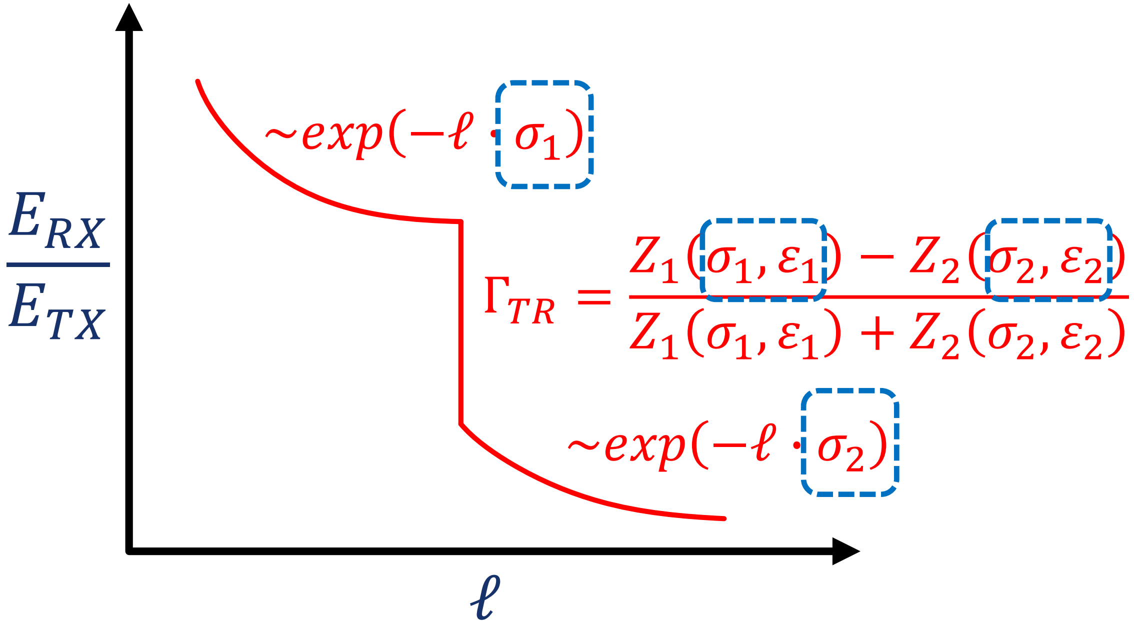




Propagating Wave Electromagnetics

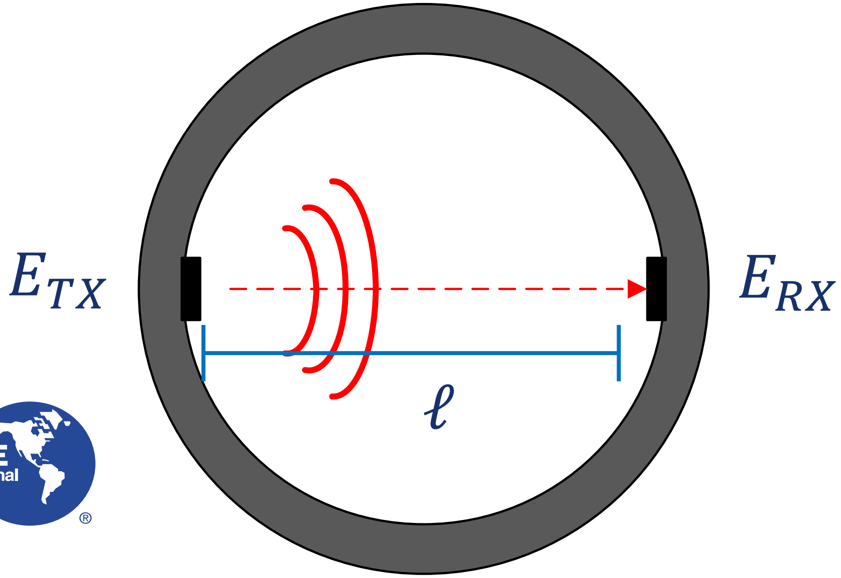
- Quantify σ via attenuation and reflection/transmission off of fluid interfaces
  - Impedance differences due to Δσ,Δε ➔ reflection/transmission
  - Tomographic imaging with multiple TX and RX paths

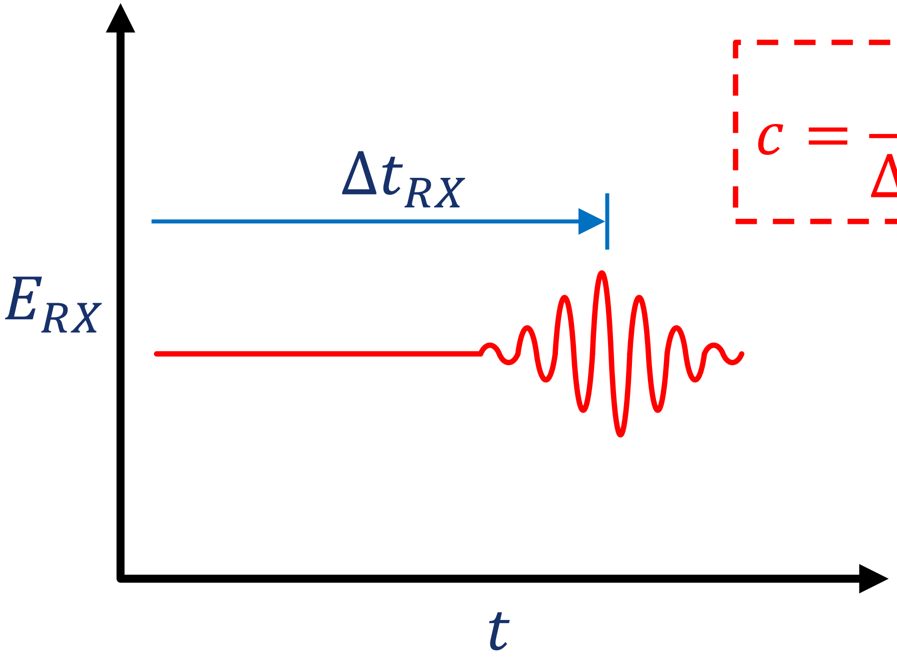




Propagating Wave Electromagnetics

- Quantify ε via propagation speed of pulse through fluid
  - Speed of EM wave $c \sim {}^{1}/_{\sqrt{\varepsilon}}$
  - Tomographic imaging with multiple TX and RX paths

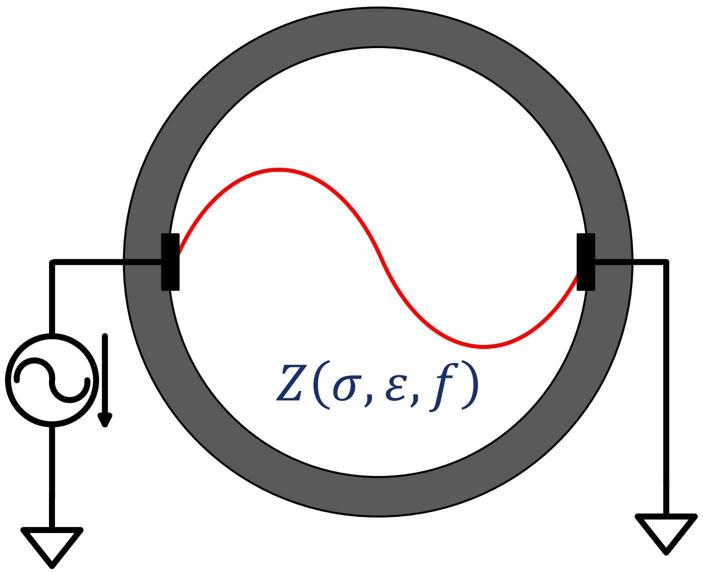


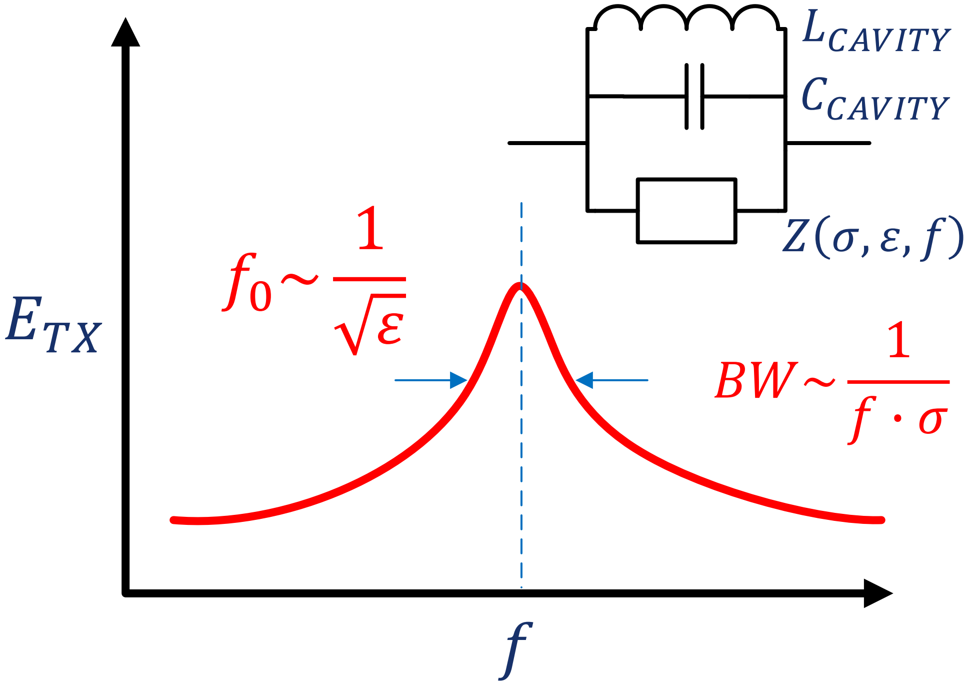


$$c = \frac{\ell}{\Delta t_{RX}} \sim {}^{1}/_{\sqrt{\varepsilon}}$$

Propagating Wave Electromagnetics

- Quantify σ and ε via characteristic frequency response from resonator
  - Resonant response due to geometry of the cavity & propagating mode
  - EM properties of the fluid define the characteristic response





Propagating Wave Electromagnetics

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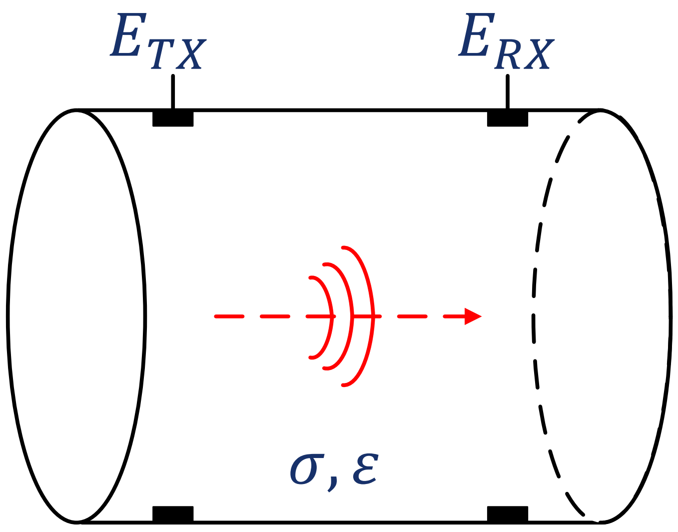
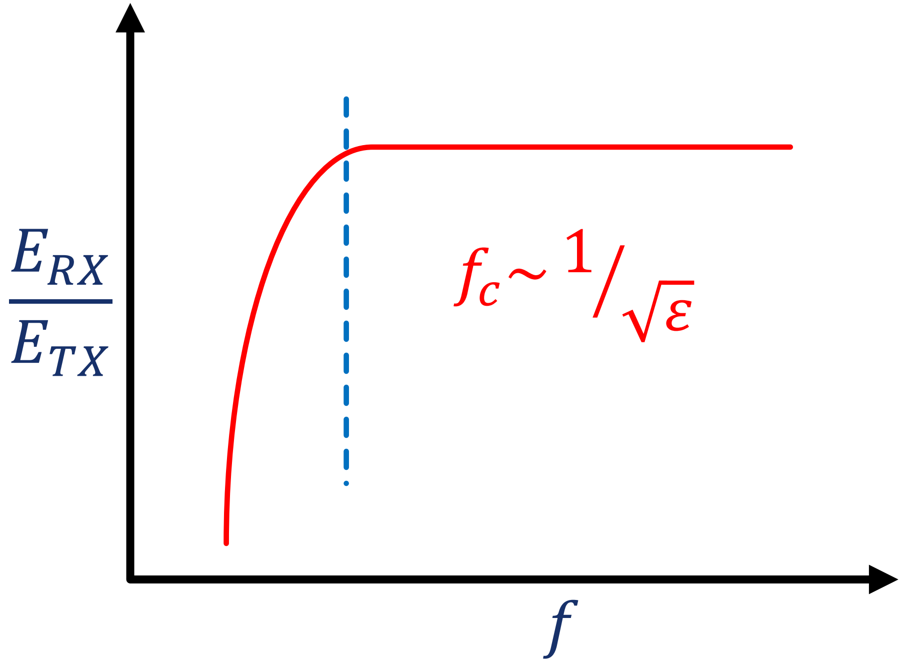
- Quantify ε via propagation cutoff frequency
  - Pipe & fluid acts as a transmission line
  - Characteristic cutoff frequency where modes no longer propagate





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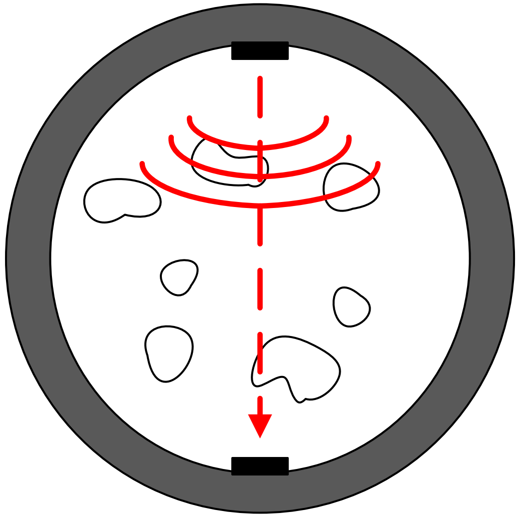
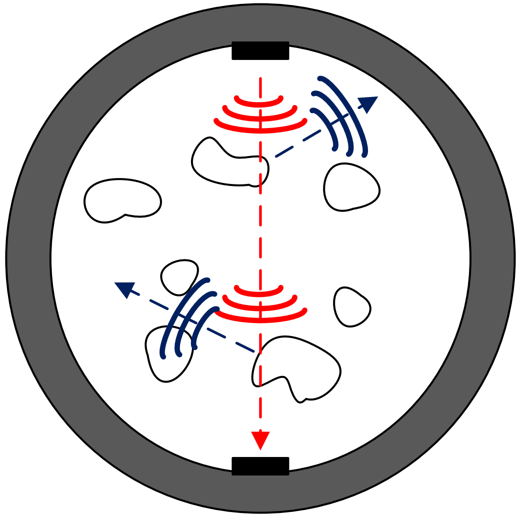
Propagating Wave Electromagnetics

- Wavelength of the EM wave is critical in this sensing domain
  - Wavelength is $\lambda_{MODE} \sim 1/\sqrt{\varepsilon} \cdot c_0/f$, e.g. 3GHz wave in brine $\approx 10cm$
  - Scattering losses occur at interfaces and effective medium approximation breaks down, e.g. phase inversion region

$\lambda_{MODE} \gg \ell_{FEATURE}$



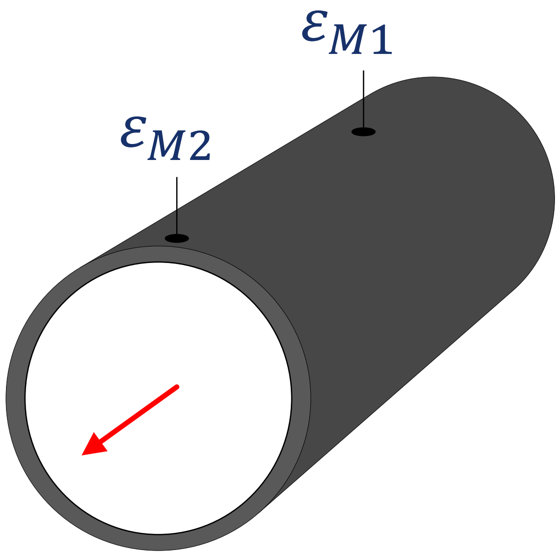
$\lambda_{MODE}/2 \approx \ell_{FEATURE}$

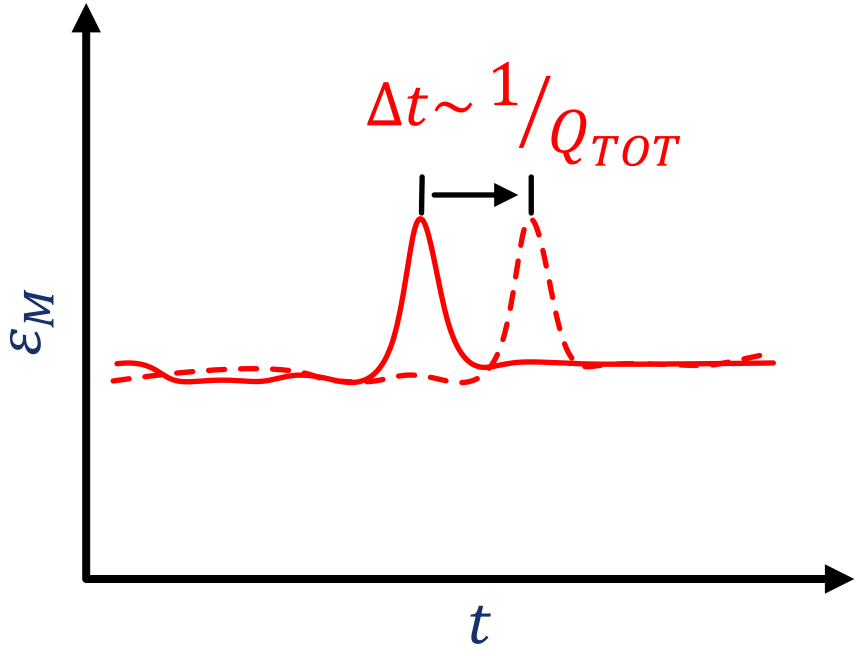


Propagating Wave Electromagnetics

- Flow rate estimation via cross correlation, similar to DC & Time Varying EM

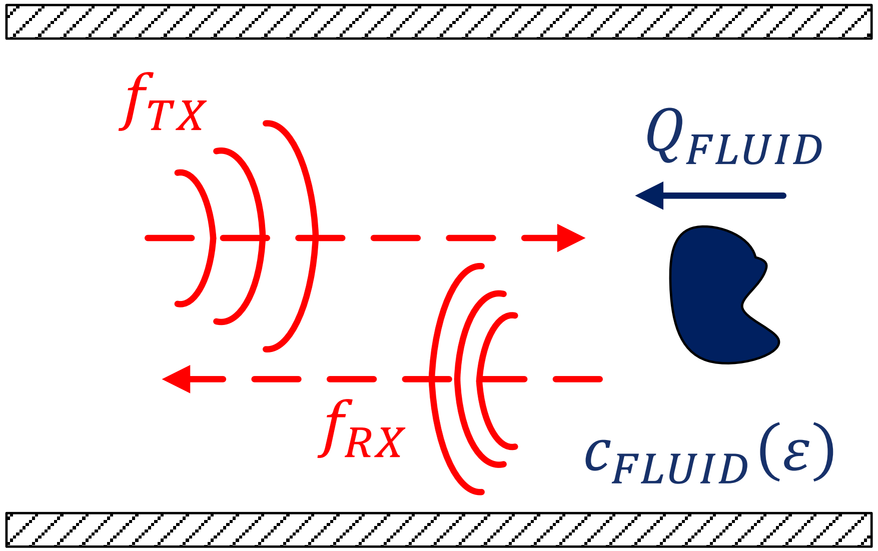
$$Q_{TOT} = Q_{TOT} \cdot \phi_O + Q_{TOT} \cdot \phi_W + Q_{TOT} \cdot \phi_G$$





Propagating Wave Electromagnetics

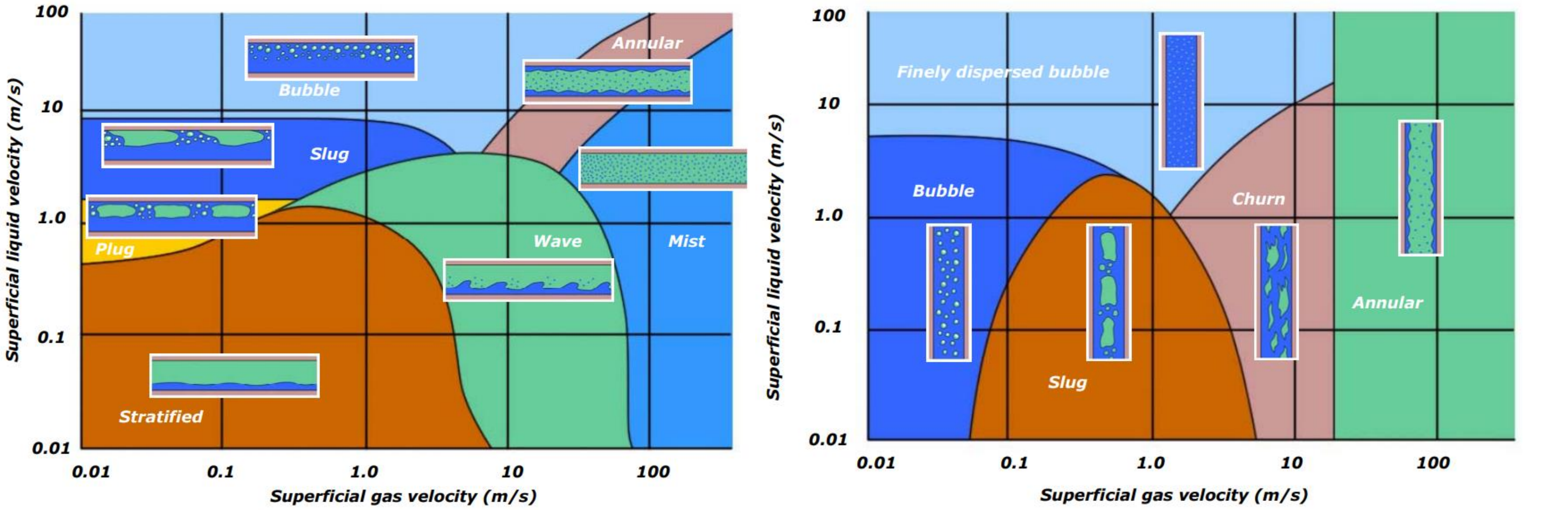
- Flow rate estimation via doppler frequency shift
  - Moving interfaces in fluid modify the frequency of the source wave
  - Reflected frequency f_{RX} ↑ as reflector moves towards source f_{TX}



$$Q_{FLUID} \sim \frac{(f_{RX} - f_{TX}) \cdot c_{FLUID}}{2 \cdot f_{TX}}$$

Propagating Wave Electromagnetics

- Phase inversion region leads to model breakdown & scattering loss
- Well-mixed homogeneous flows are ideal. Other flow regimes require greatly increased model complexity



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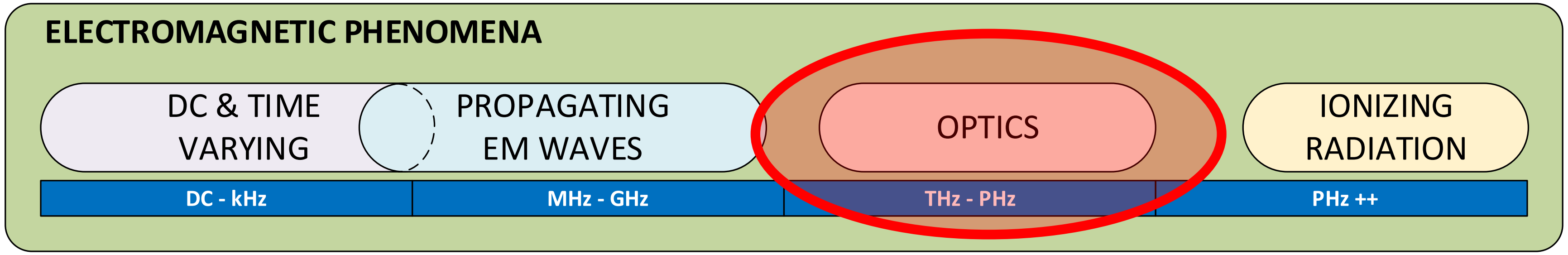
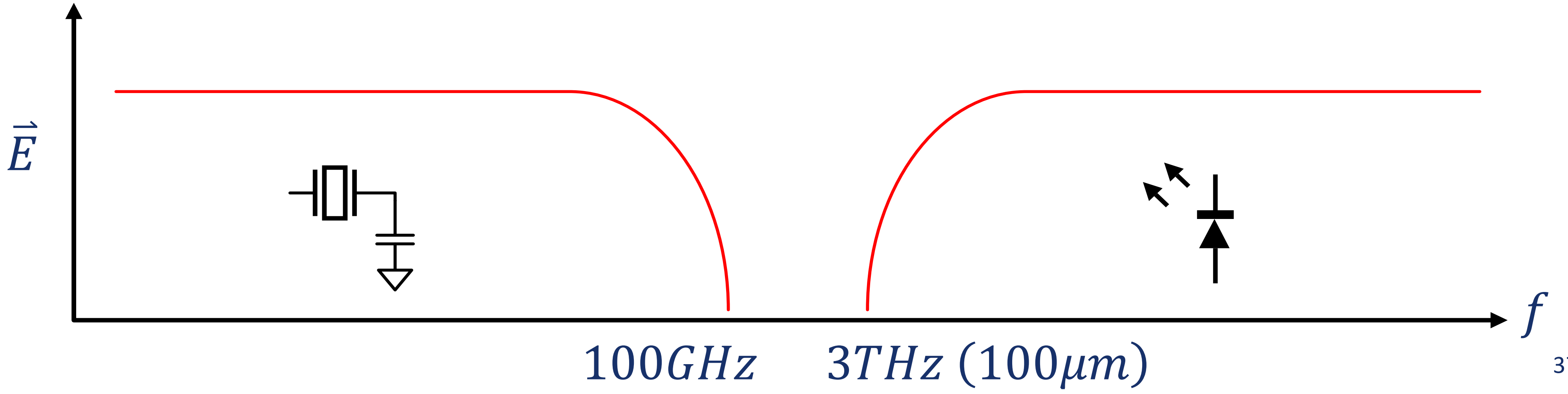
Overview of Electromagnetic Sensing

- Optical domain of EM Sensing
  - Frequency range spans $\sim 3THz$ to $\sim 1PHz$
  - Switch discussion to wavelength in this domain, i.e. $3THz \approx 100\mu m$ and $1PHz \approx 300nm$



The Electronic and Optical Gap

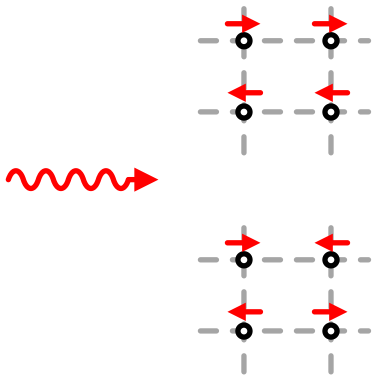
- Gap in source power between $\sim 100GHz$ and $\sim 3THz$
  - Electronic oscillator sources: stray capacitance limiting energy output, e.g. low pass filter
  - Optical emission sources: entropy suppressing radiation, e.g. phonon absorption near $k_B T$



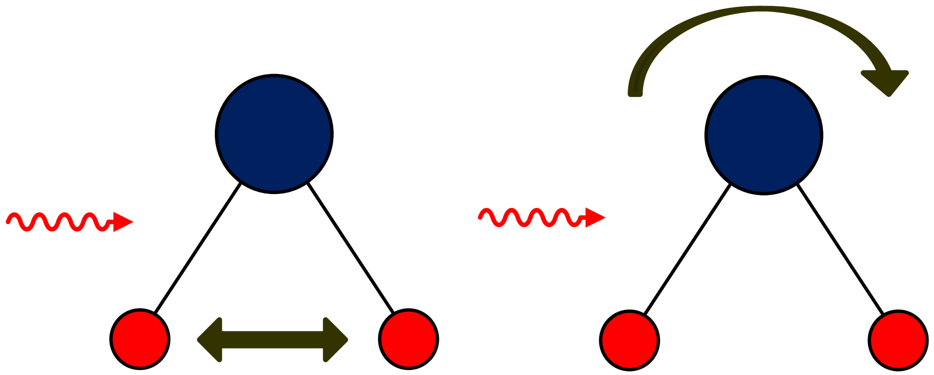
Optical Sensing

- In the optical wavelength region we see energy absorption from a variety of physical phenomena: interatomic vibrations (phonons), rotational modes of molecules, and valence electron transitions

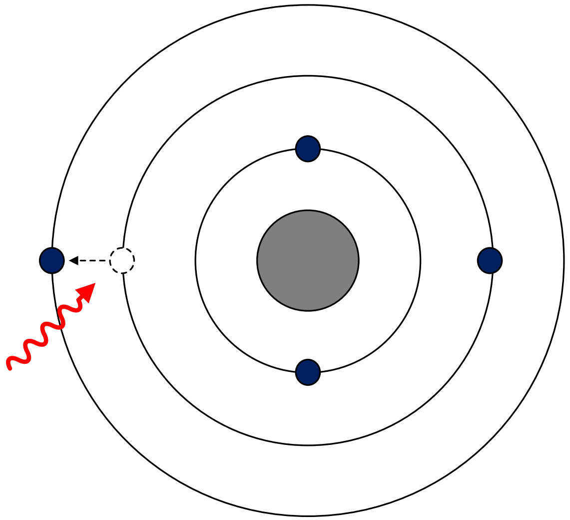
Phonons



Molecular Rotations

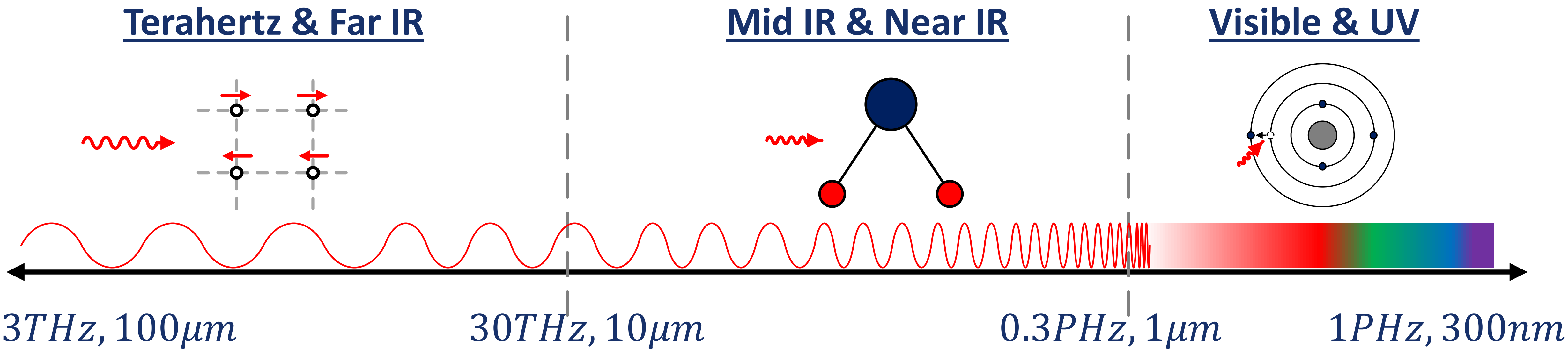


Valence Electron Transitions



Optical Sensing

- In this sensing domain, we discriminate ϕ_O, ϕ_W, ϕ_G by their unique spectral absorption response in various wavelength regions



Optical Sensing

- Spectral absorption (α) is dispersive, e.g. changes with wavelength
- Can now utilize two independent equations to determine ϕ_O, ϕ_W, ϕ_G

$$1 = \phi_O + \phi_W + \phi_G$$

$$S_1 = f_1(\phi_O, \phi_W, \phi_G)$$

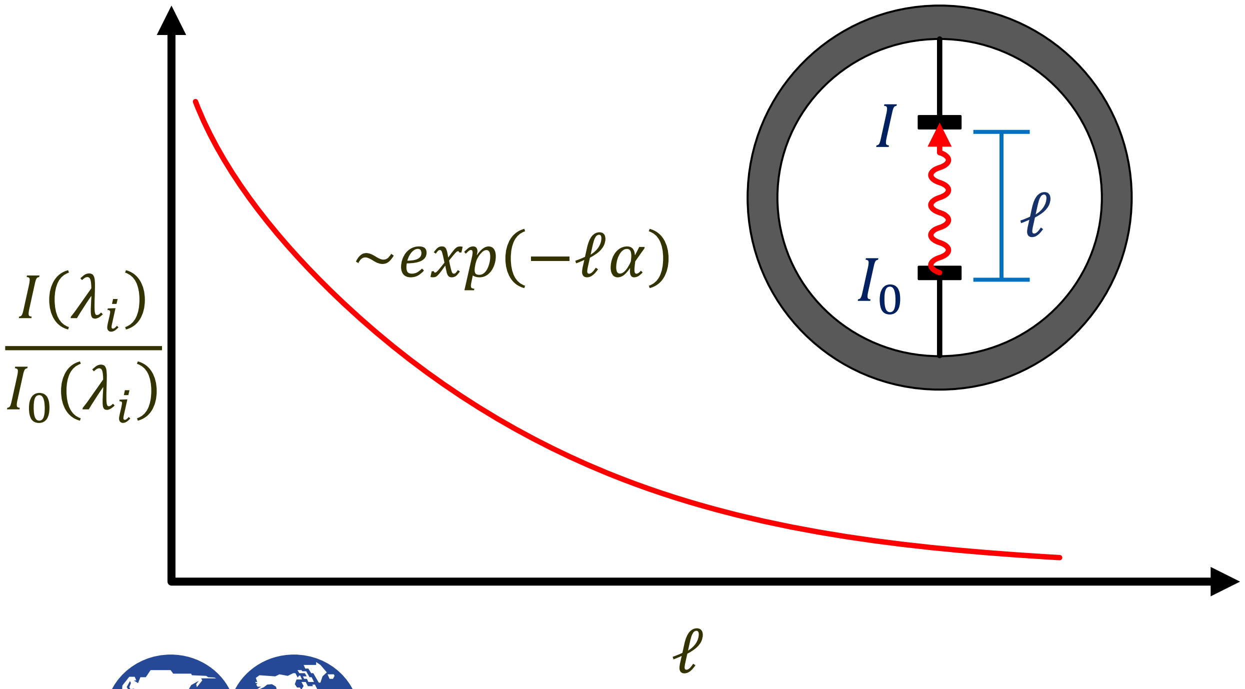
$$S_2 = f_2(\phi_O, \phi_W, \phi_G)$$

$$\Rightarrow \begin{cases} 1 = \phi_O + \phi_W + \phi_G \\ \alpha(\lambda_1) = \phi_O \alpha_O(\lambda_1) + \phi_W \alpha_W(\lambda_1) + \phi_G \alpha_G(\lambda_1) \\ \alpha(\lambda_2) = \phi_O \alpha_O(\lambda_2) + \phi_W \alpha_W(\lambda_2) + \phi_G \alpha_G(\lambda_2) \end{cases}$$

$$Q_{TOT} = Q_{TOT} \cdot \phi_O + Q_{TOT} \cdot \phi_W + Q_{TOT} \cdot \phi_G$$

Optical Sensing

- Mixing rule for absorption derived from Beer Lambert Law for multiple media along ray path



$$I(\lambda_1) = I_0(\lambda_1)exp[-\ell \cdot \alpha(\lambda_1)]$$

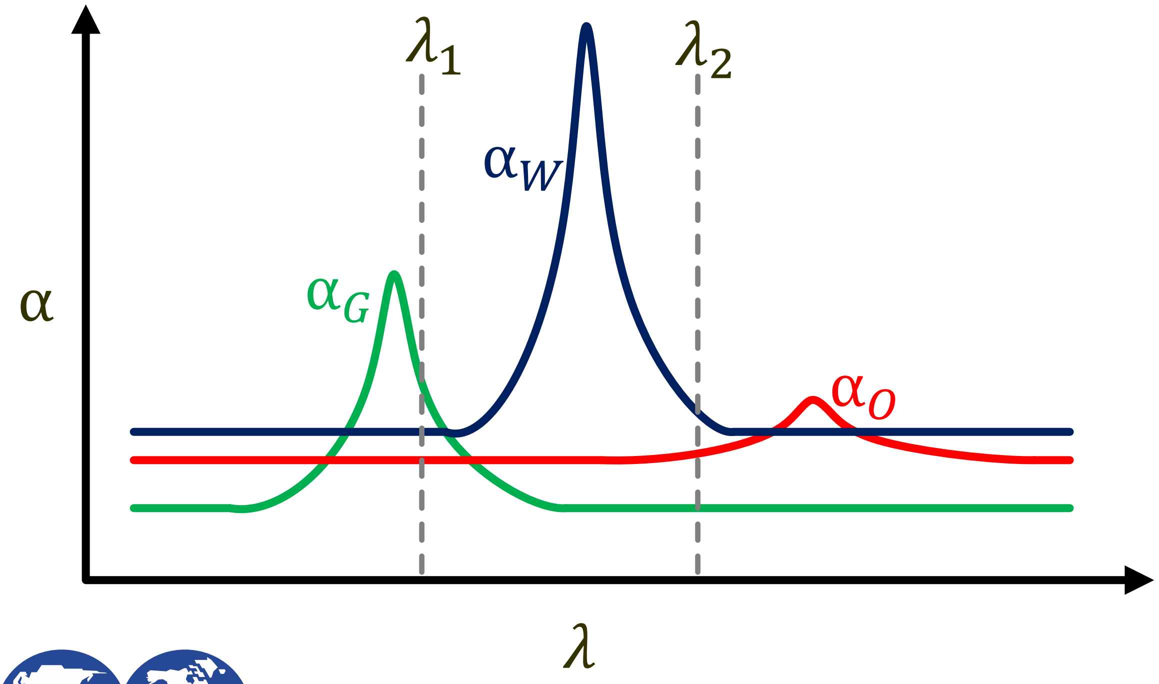
$$I(\lambda_2) = I_0(\lambda_2)exp[-\ell \cdot \alpha(\lambda_2)]$$

$$\alpha(\lambda_1) = \phi_O\alpha_O(\lambda_1) + \phi_W\alpha_W(\lambda_1) + \phi_G\alpha_G(\lambda_1)$$

$$\alpha(\lambda_2) = \phi_O\alpha_O(\lambda_2) + \phi_W\alpha_W(\lambda_2) + \phi_G\alpha_G(\lambda_2)$$

Optical Sensing

- Mixing rule for spectral absorption: Beer Lambert Law



$$I(\lambda_1) = I_0(\lambda_1) exp[-\ell \cdot \alpha(\lambda_1)]$$

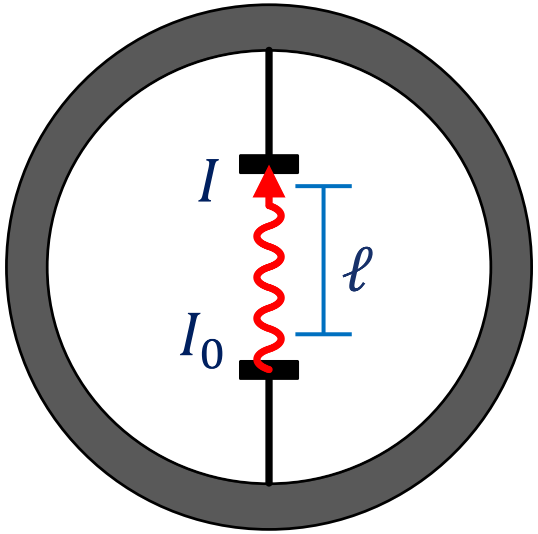
$$I(\lambda_2) = I_0(\lambda_2) exp[-\ell \cdot \alpha(\lambda_2)]$$

$$\alpha(\lambda_1) = \phi_O \alpha_O(\lambda_1) + \phi_W \alpha_W(\lambda_1) + \phi_G \alpha_G(\lambda_1)$$

$$\alpha(\lambda_2) = \phi_O \alpha_O(\lambda_2) + \phi_W \alpha_W(\lambda_2) + \phi_G \alpha_G(\lambda_2)$$

Optical Sensing

- Combinations of broadband and narrowband emitters and receivers
- Exponential loss from absorption ➔ systems typically have optical emitters and receivers near each other



$$\alpha_W(\lambda = 5\mu m) \approx 10^4\ m^{-1}$$

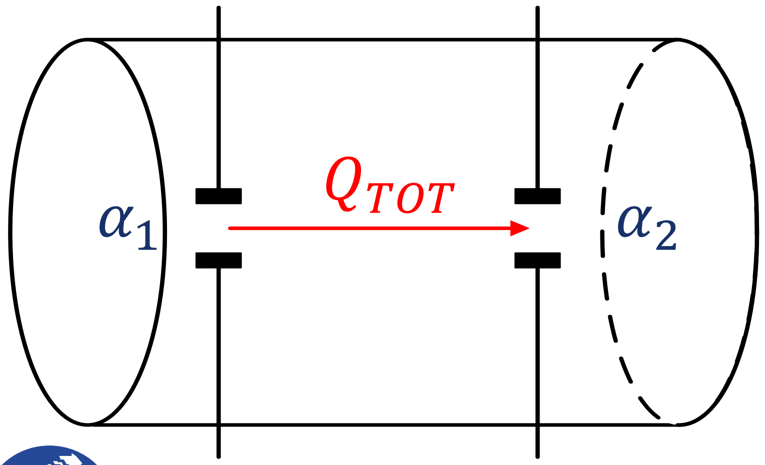
$$\ell = 0.5\ mm$$

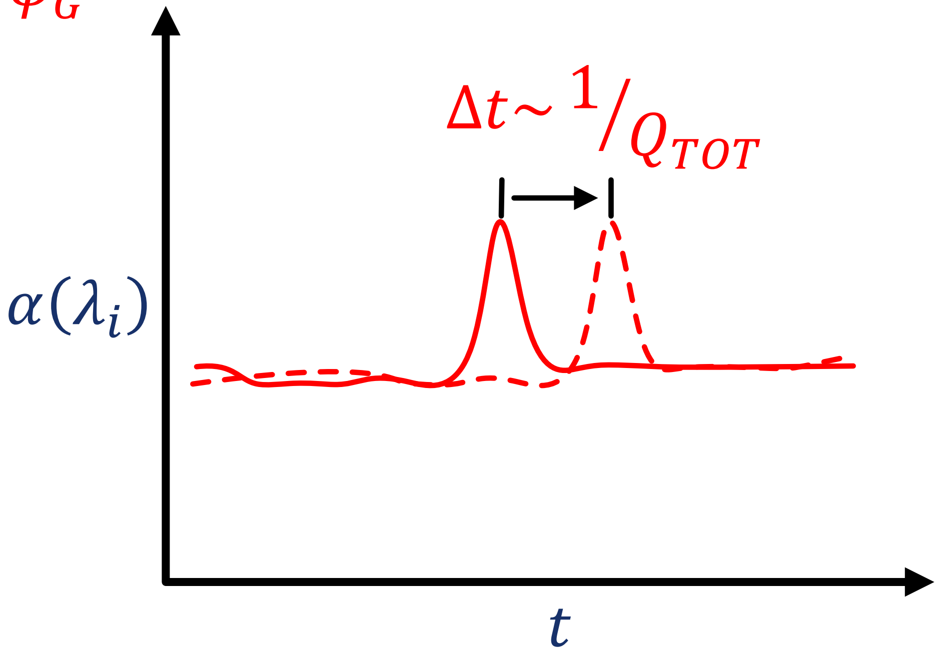
$$\frac{I}{I_0} \cong 0.7\%$$

Optical Sensing

- Flow rate estimation via cross correlation, similar to Propagating Wave EM
- Added difficulty due to point sampling of fluid with optical sensing

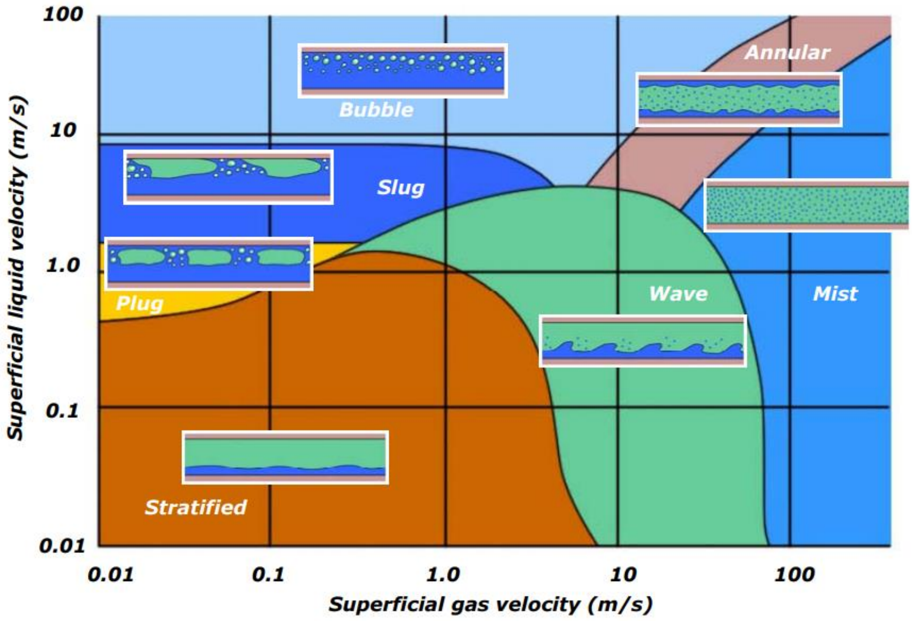
$$Q_{TOT} = Q_{TOT} \cdot \phi_O + Q_{TOT} \cdot \phi_W + Q_{TOT} \cdot \phi_G$$

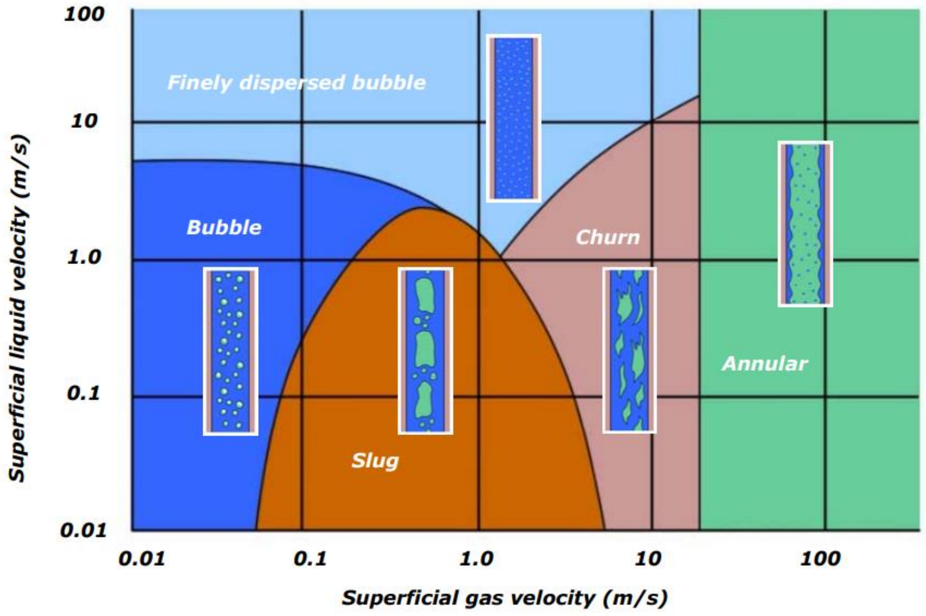




Optical Sensing

- Ideal response in homogenous mixtures, minimal cross section to interrogate to represent the total flow volume
- Less absorption loss in high GVF flows

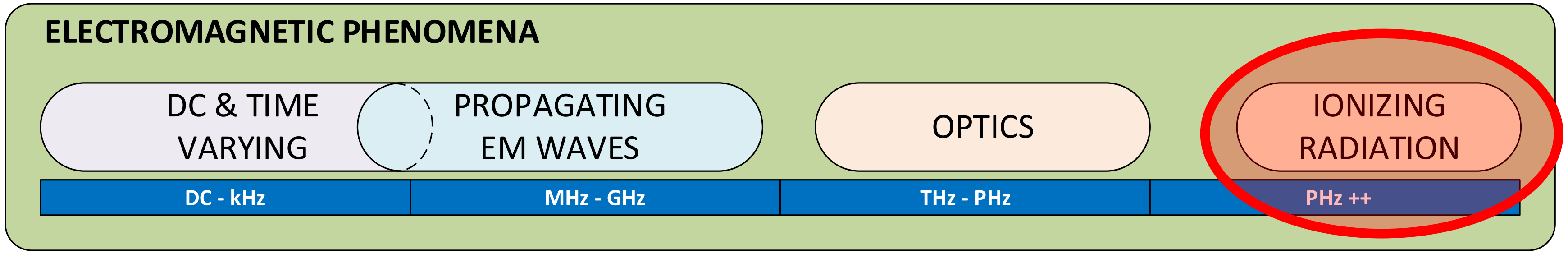




“Handbook of Multiphase Metering, NFOGM”
https://nfogm.no/wp-content/uploads/2014/02/MPFM_Handbook_Revision2_2005_ISBN-82-91341-89-3.pdf

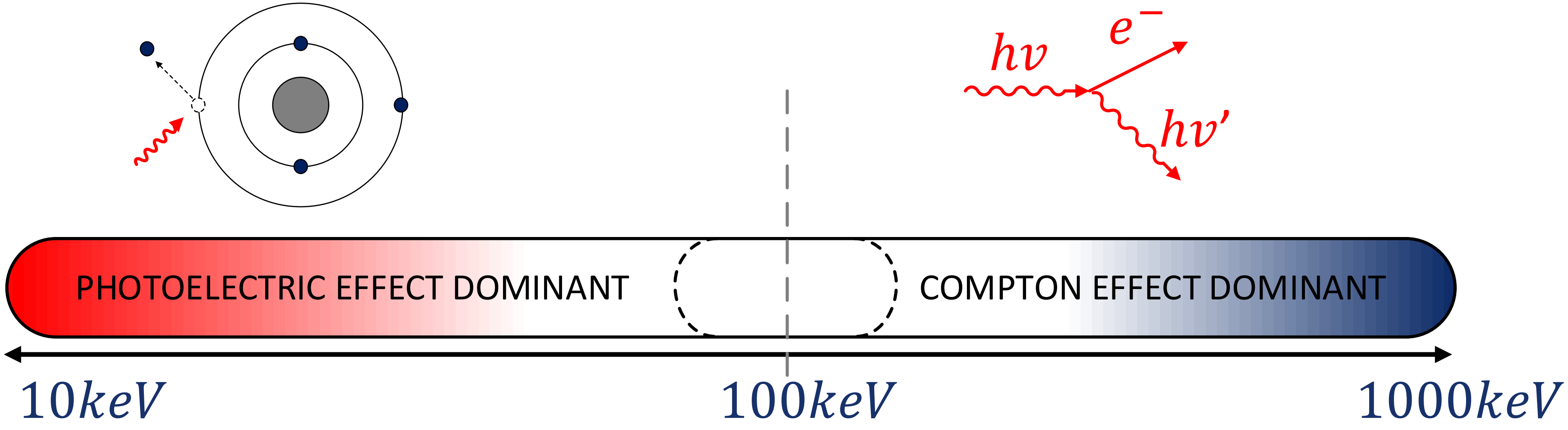
Overview of Electromagnetic Sensing

- Ionizing Radiation domain of EM Sensing
  - Frequency range spans $\sim 200PHz$ and beyond
  - Switch discussion to energy (eV) in this domain, i.e. $200PHz \approx 1keV$



Ionizing Radiation

- In this high-energy particle range, photon energy is high enough to rearrange or outright remove electrons within atoms and molecules
- Absorption and/or re-emission via Photoelectric or Compton effect



Ionizing Radiation

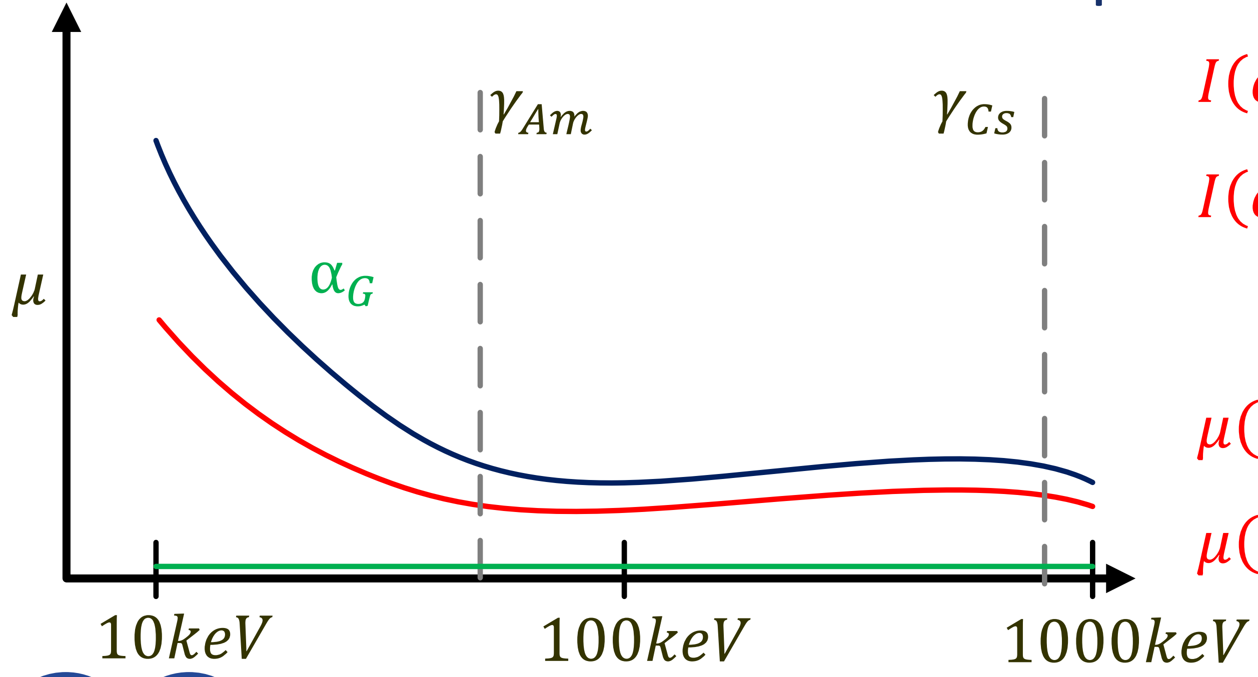
- Atomic interaction effects (μ) are dispersive, e.g. changes with energy
- Similar to optical sensing domain, utilize two independent equations to determine ϕ_O, ϕ_W, ϕ_G

$$\left.\begin{aligned} 1 &= \phi_O + \phi_W + \phi_G \\ S_1 &= f_1(\phi_O, \phi_W, \phi_G) \\ S_2 &= f_2(\phi_O, \phi_W, \phi_G) \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} 1 &= \phi_O + \phi_W + \phi_G \\ \mu(e_1) &= \phi_O \mu_O(e_1) + \phi_W \mu_W(e_1) + \phi_G \mu(e_1) \\ \mu(e_2) &= \phi_O \mu_O(e_2) + \phi_W \mu_W(e_2) + \phi_G \mu_G(e_2) \end{aligned}\right.$$

$$Q_{TOT} = Q_{TOT} \cdot \phi_O + Q_{TOT} \cdot \phi_W + Q_{TOT} \cdot \phi_G$$

Ionizing Radiation

- Similar to Optical sensing domain, mixing rule for absorption derived from Beer Lambert Law for multiple media along ray path



$$I(e_1) = I_0(e_1)exp[-\ell \cdot \mu(e_1)]$$

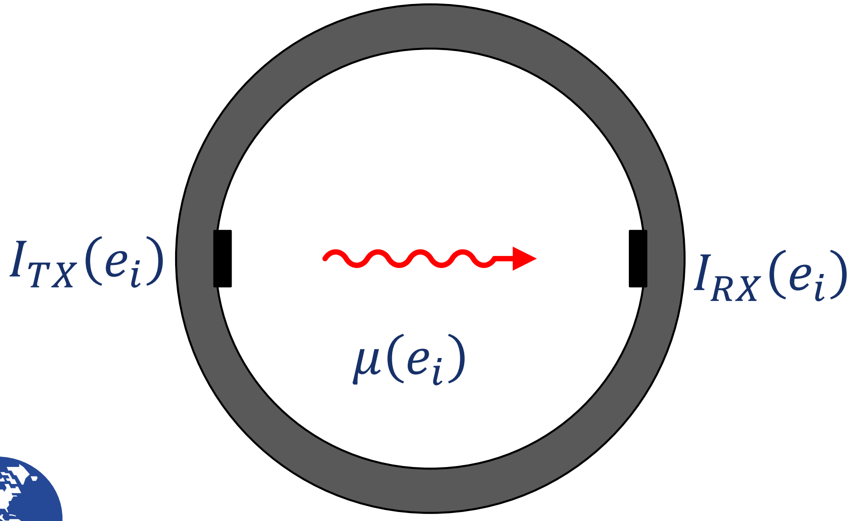
$$I(e_2) = I_0(e_2)exp[-\ell \cdot \mu(e_2)]$$

$$\mu(e_1) = \phi_O\mu_O(e_1) + \phi_W\mu_W(e_1) + \phi_G\mu_G(e_1)$$

$$\mu(e_2) = \phi_O\mu_O(e_2) + \phi_W\mu_W(e_2) + \phi_G\mu_G(e_2)$$

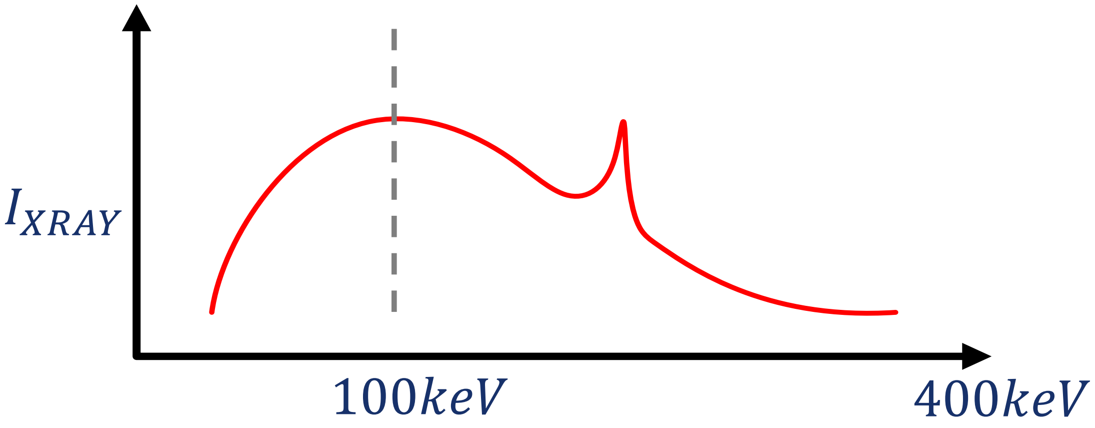
Ionizing Radiation

- Typically in a transmission-style measurement
- Chemical sources which emit x-ray and gamma ray photons (narrowband emission) or electronic x-ray sources (broadband emission)



Isotope	γ-ray Emission (keV)	x-ray Emission (keV)
^{241}Am	60	13.9, 17.8
^{137}Cs	662	32.1

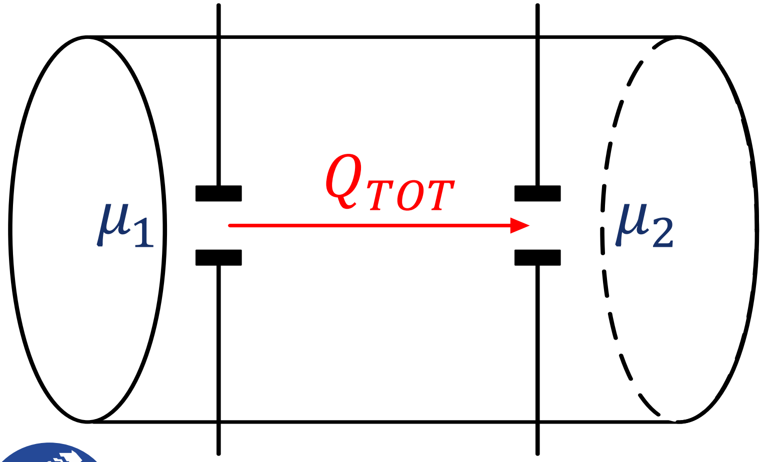
M. Wang, "Industrial Tomography" Woodhead Publishing (2015).

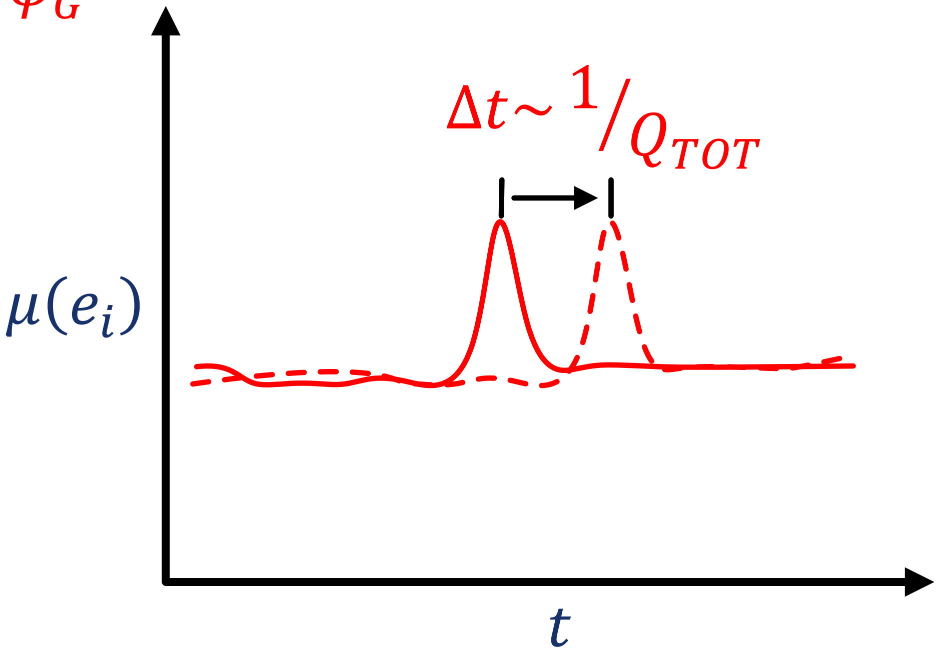


Ionizing Radiation

- Flow rate estimation via cross correlation, similar to Optical Sensing

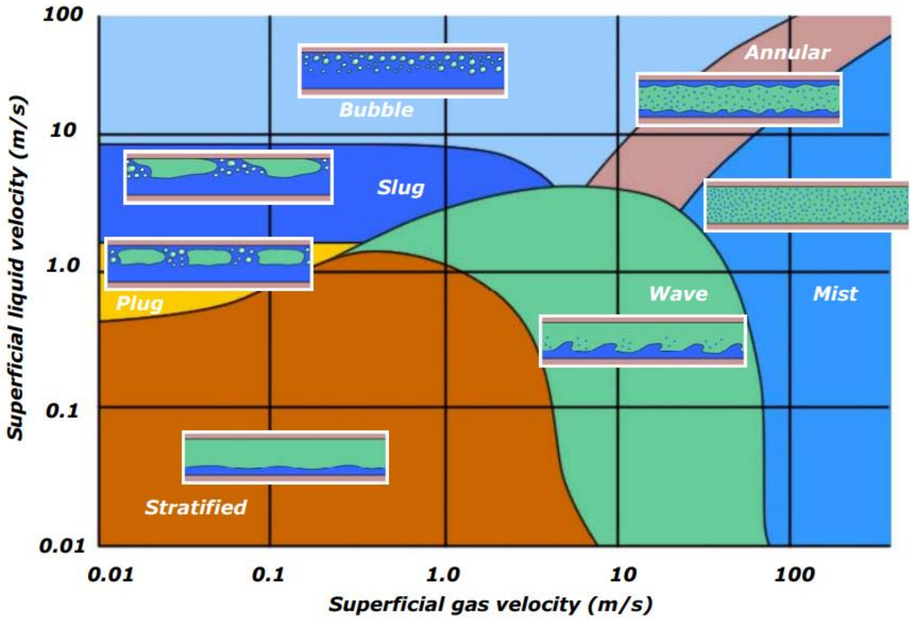
$$Q_{TOT} = Q_{TOT} \cdot \phi_O + Q_{TOT} \cdot \phi_W + Q_{TOT} \cdot \phi_G$$

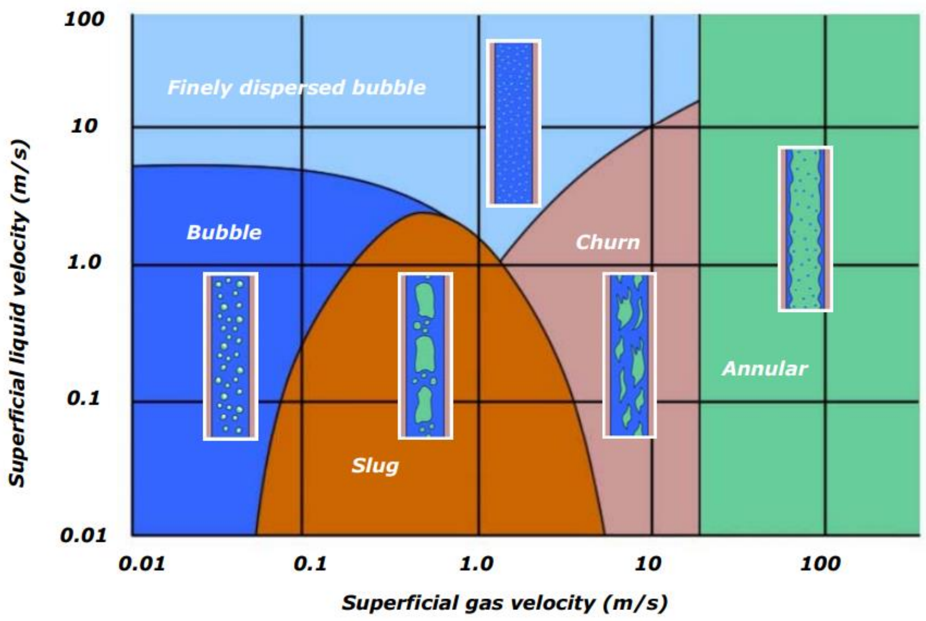




Ionizing Radiation

- Ideal response in homogenous mixtures, minimal cross section to interrogate to represent the total flow volume





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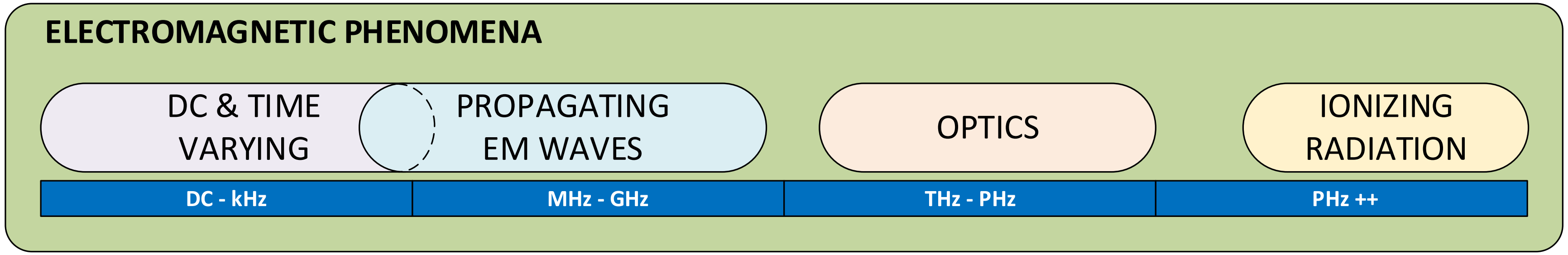
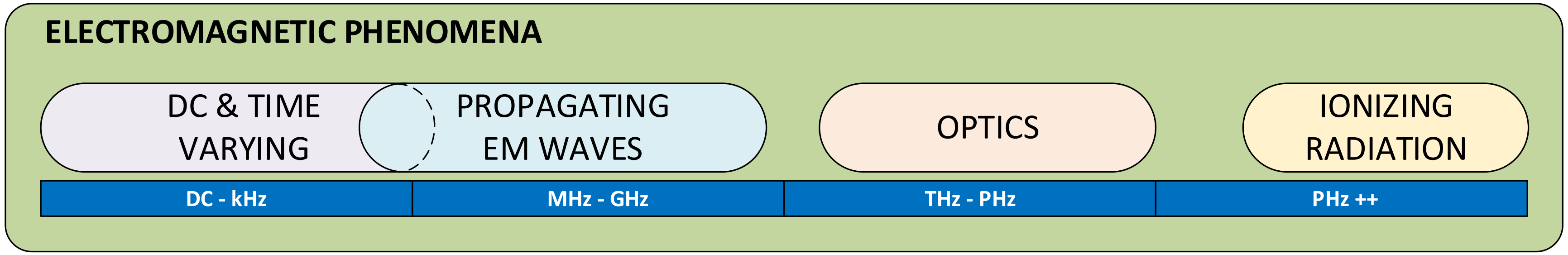
Conclusion & Acknowledgements



- Large variety electromagnetic phenomena across to discriminate phase fractions
- Limitation in available methods to directly measure flow rates
- This is not a complete list! We will cover more sensing domains in part two of this webinar series

Conclusion & Acknowledgements



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  - SPE Flow Measurement Technical Section