January 01, 2001

Nano and Microscale Particle Removal

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NANO AND MICROSCALE PARTICLE REMOVAL

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OUTLINE

- Goals and Objectives
- Approach
- Preliminary Results
  - Acoustic Streaming and Boundary Layer
  - Particle Removal Mechanism
  - Double layer
  - Effect of Particle Size and Flow Frequency
- Key Preliminary Research Results

Surface Preparation Technology Requirements -- Long Term**

YEAR	1999	2000	2002	2005	2008	2011	2014
TECHNOLOGY NODE	180nm		130nm	100nm	70nm	50nm	35nm
FEOL Particle Size(nm)	90	82.5	60	50	35	25	18
FEOL Particles (#/cm^2)	0.064	0.06	0.064	0.051	0.052	0.052	0.052
BEOL Particle Size(nm)	180	165	130	100	70	50	36
BEOL Particles (#/cm^2)	0.064	0.06	0.064	0.051	0.052	0.052	0.052
Surface Roughness (nm)	0.15	0.14	0.12	0.1	0.08	0.08	0.08
Critical surface metals(*10^9)	9	7	4.4	2.5	--	--	--
Organics (*10^{13} atoms/cm^2)	7.3	6.6	5.3	4.1	--	--	--

** ---- The International Technology Roadmap for Semiconductors, 2000

Goals and Objectives

- Develop an effective nanoscale particle removal technique using acoustic streaming.
- Provide a fundamental understanding of the removal mechanism that will be experimentally verified.
- Experimentally measure particle removal of particles in the size range of 10-100 nm from semiconductor wafers.
- Evaluate effect of streaming flow frequency, velocity amplitude and particle size and particle/substrate composition on the removal efficiency experimentally and numerically.

Approach

- *Fundamental Approach*
- *Experimental and modeling approach to determine, understand and predict:*
  - *Particle Removal Mechanism*
  - *Cleaning Efficiency, F{R, V, F_{ad}, etc.)*
  - *Cleaning tank Geometry (single, batch, etc.)*
  - *Optimum cleaning conditions*
  - *Cleaning technology limits with shrinking particle and defect size*

Approach

- ***Fundamental Approach***
- **Key Particle Removal Parameters**
  - flow frequency
  - velocity (pressure) amplitude
  - Particle size
  - Particle composition
  - Particle shape
  - Particle deformation and contact area
  - Double layer effect on removal
  - Cleaning liquid surface tension
  - Surface and particle surface energy (hydrophilic or hydrophobic)

MEGASONIC CLEANING

- **Megasonic sound wave:**

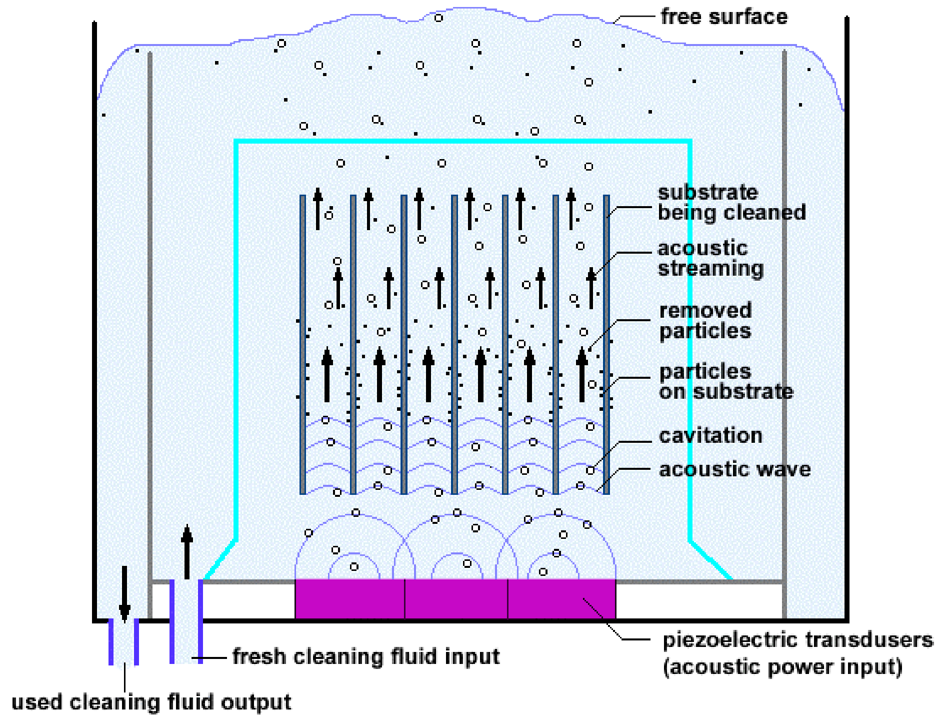
$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

$$p(x,t) = p_0 \sin(kx - \omega t + \Phi)$$

$$u(x,t) = u_0 \sin(kx - \omega t + \Phi)$$

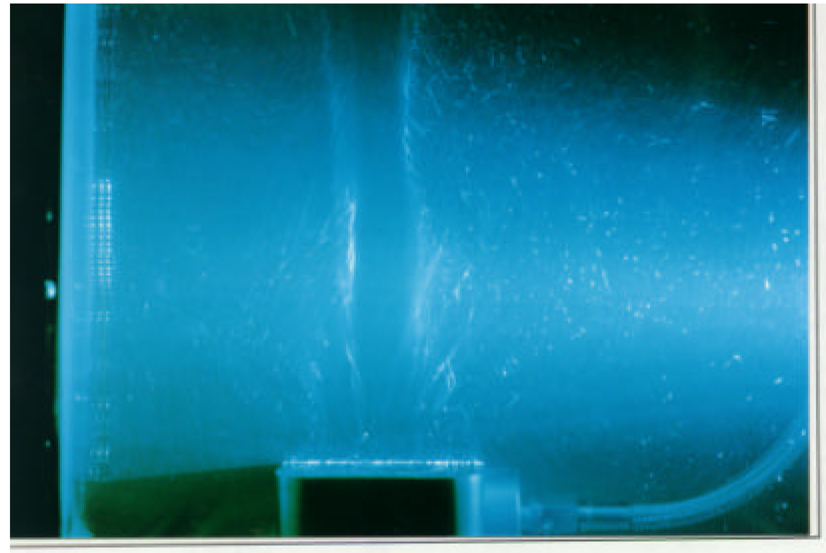
- **Megasonic power intensity:**

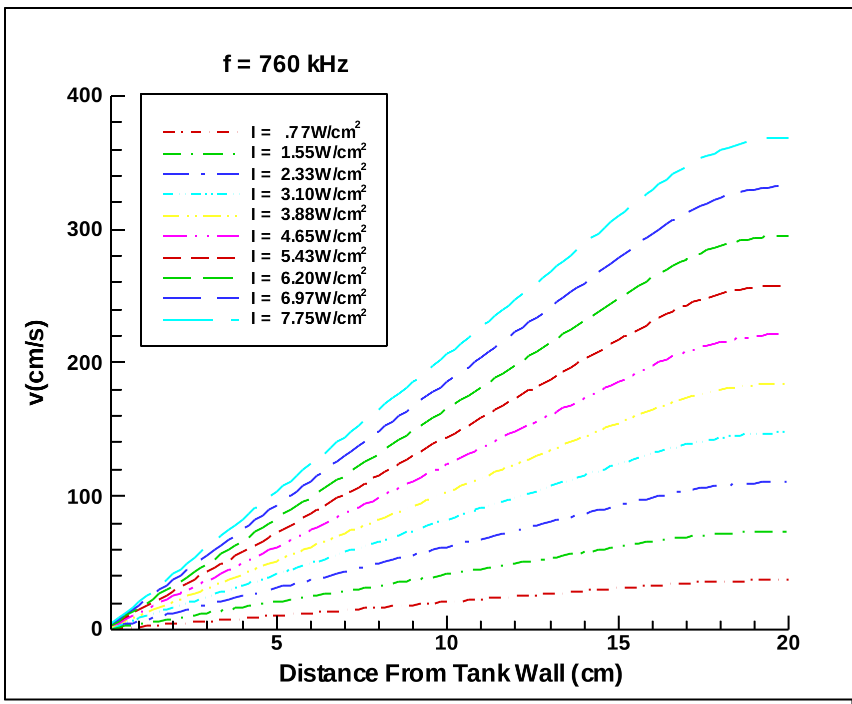
$$I = \frac{p_0^2}{2\rho c}$$

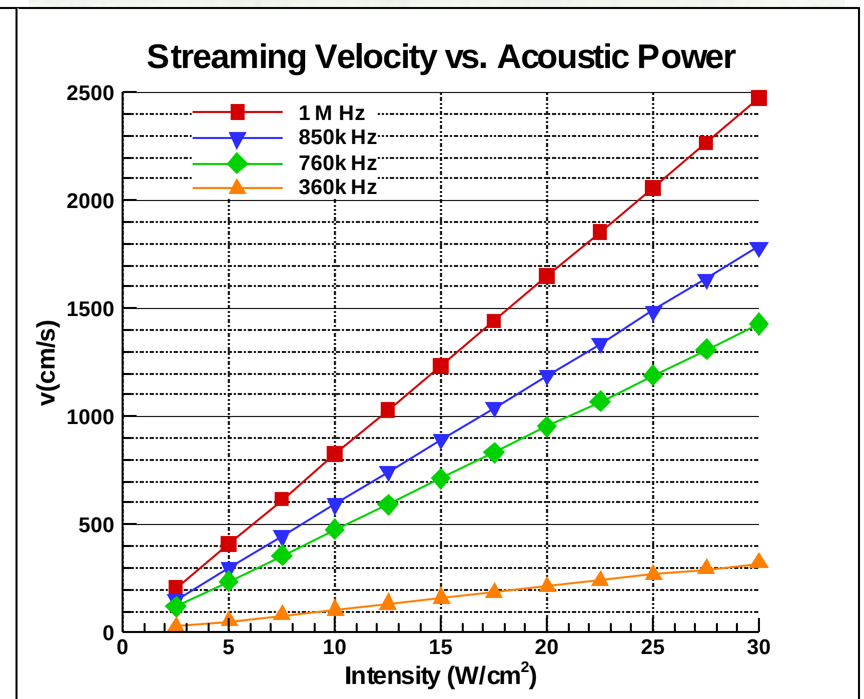


Megasonic Cleaning Mechanism

ACOUSTIC STREAMING







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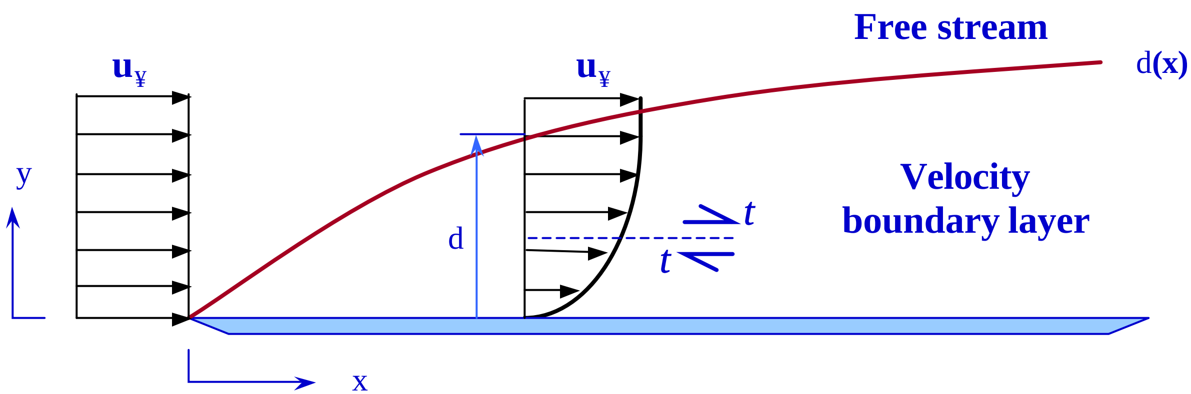
PARTICLE REMOVAL

- Nano-scale particles will be a challenge to current cleaning techniques.

- The most widely used cleaning techniques:
  - ✓ non-contact method (megasonic cleaning)
  - ✓ contact cleaning method (brush scrubbers)

- The two basic elements that need to be understood are :
  - ✓ Particle Adhesion
  - ✓ Particle Removal

Boundary Layer Thickness



Velocity boundary layer on a flat plate

- **Acoustic boundary layer thickness**:

$$d_{ac} = \left(\frac{2n}{w}\right)^{\frac{1}{2}}$$

in water, f=850KHz, δ_{ac}=0.61μm

f=760KHz, δ_{ac}=0.65μm

f=360KHz, δ_{ac}=0.94μm

- **The hydrodynamic boundary layer thickness**:

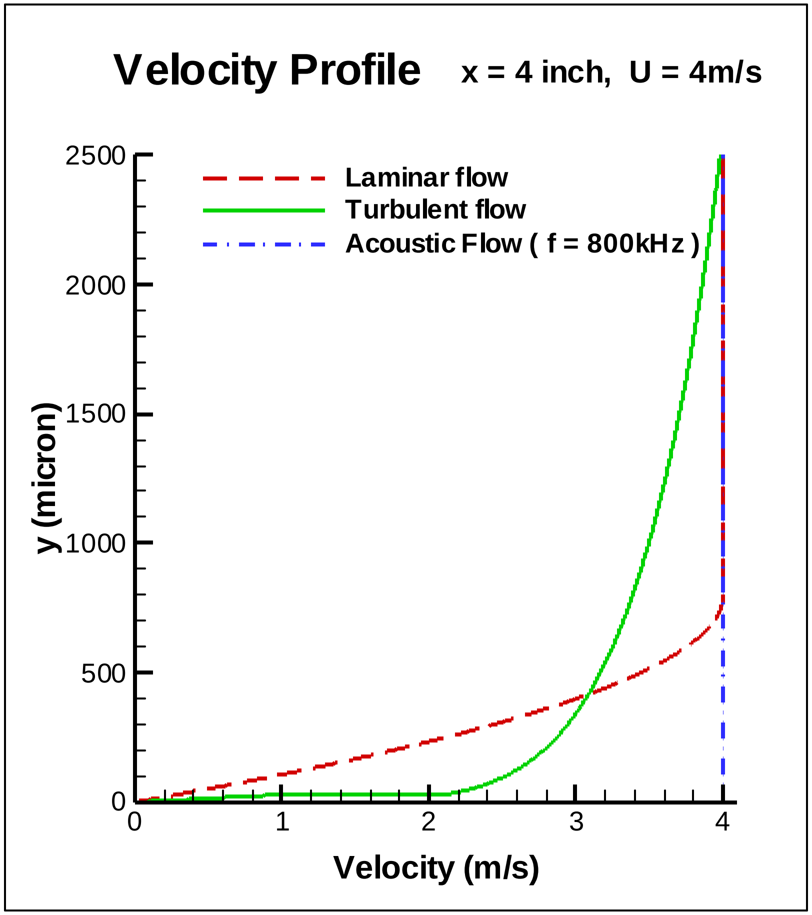
$$d_H = 0.16\left(\frac{n}{Ux}\right)^{\frac{1}{7}} \cdot x$$

in water, u=4m/s, at center of the wafer,

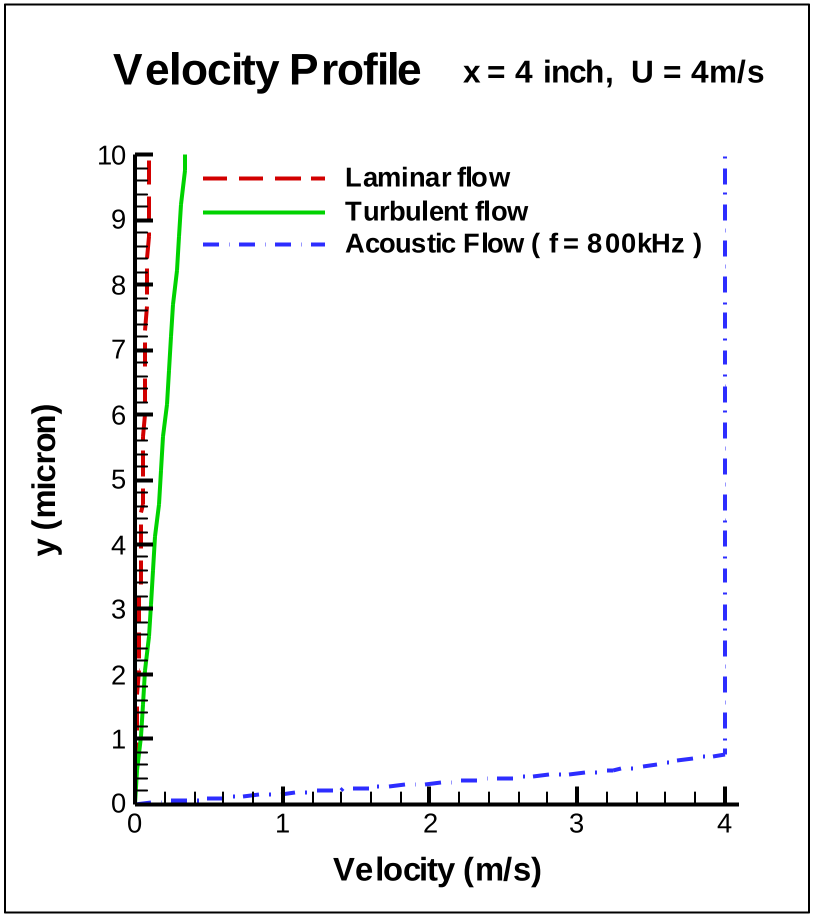
δ_H=2570 μm

Velocity Profile in a Boundary Layer

y = 0~2500 micron



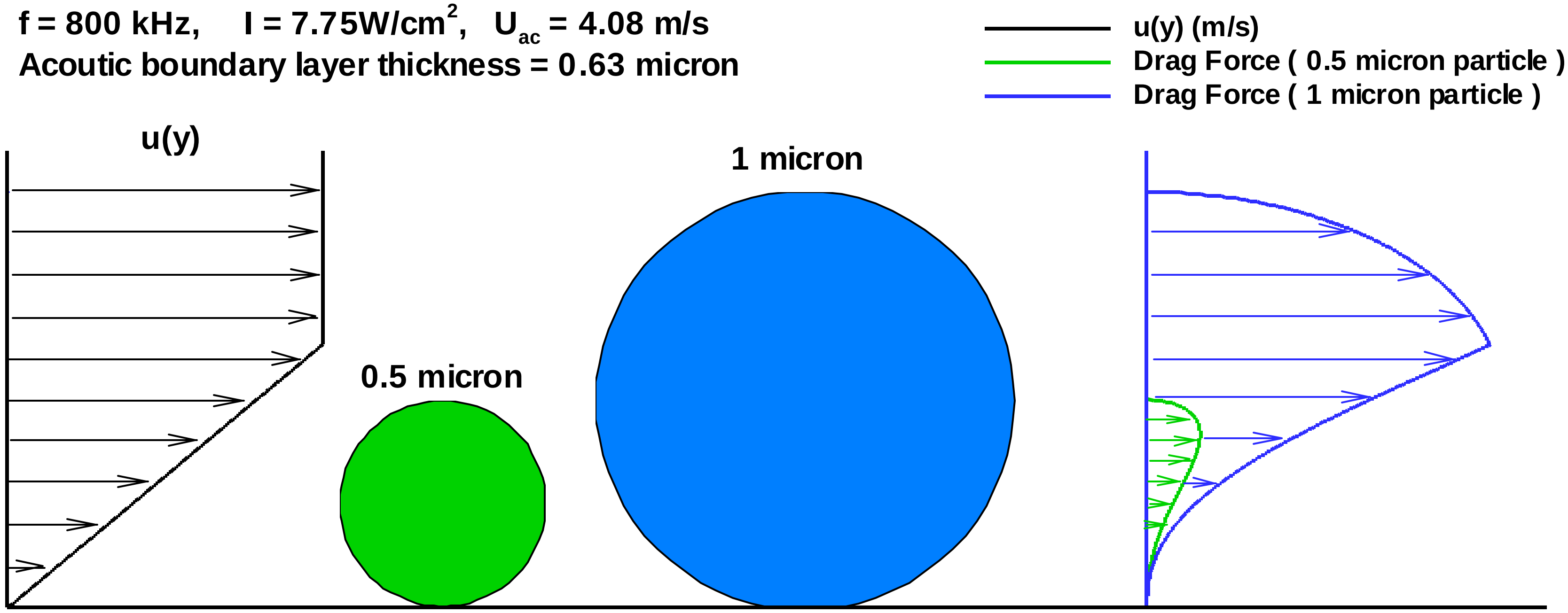
y = 0~10 micron



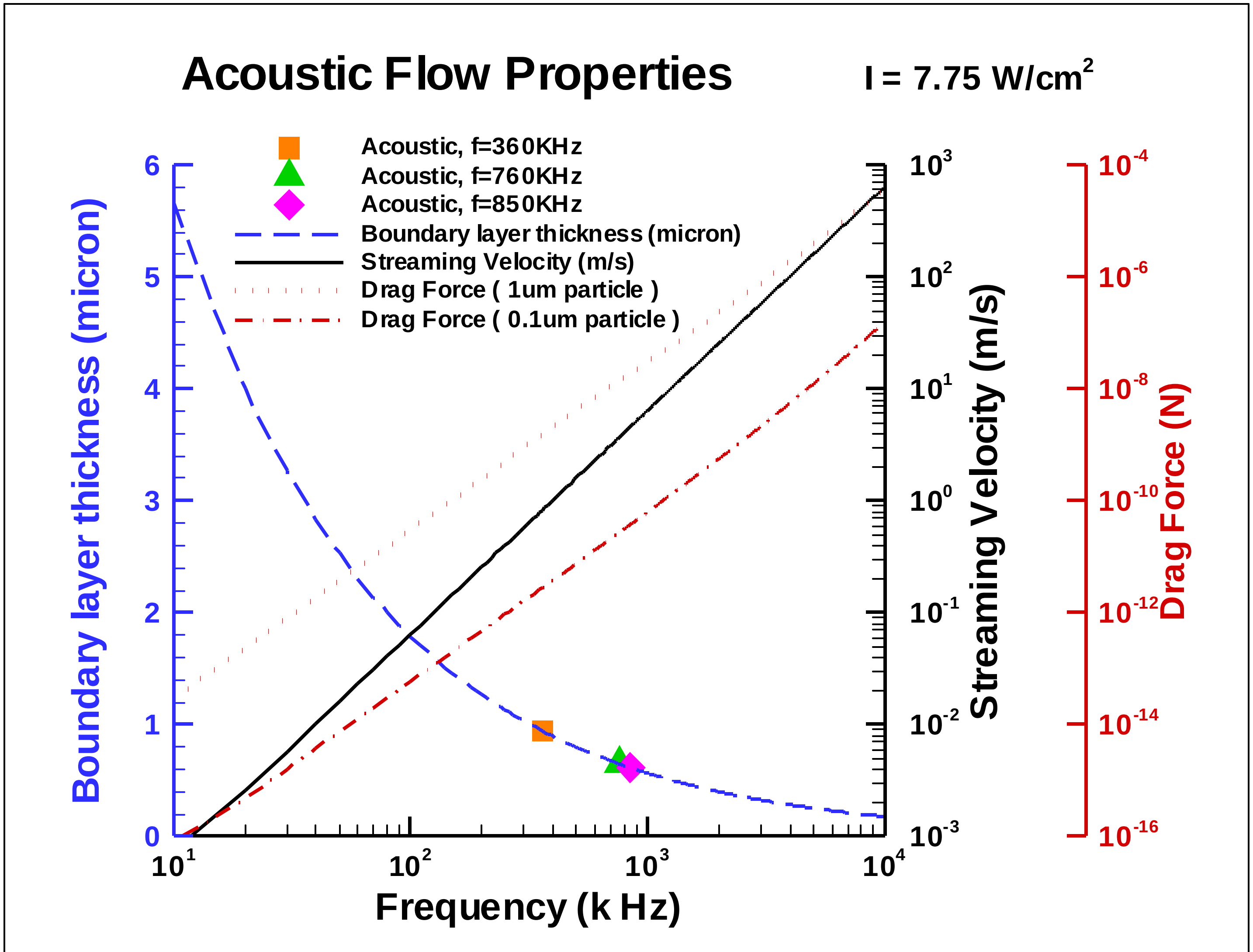
Drag Force Distribution on a Particle

$$F_D = C_D r \frac{u_i^2}{2} A_i$$

f = 800 kHz, I = 7.75W/cm², U_{ac} = 4.08 m/s
Acoutic boundary layer thickness = 0.63 micron



Effects of Frequency



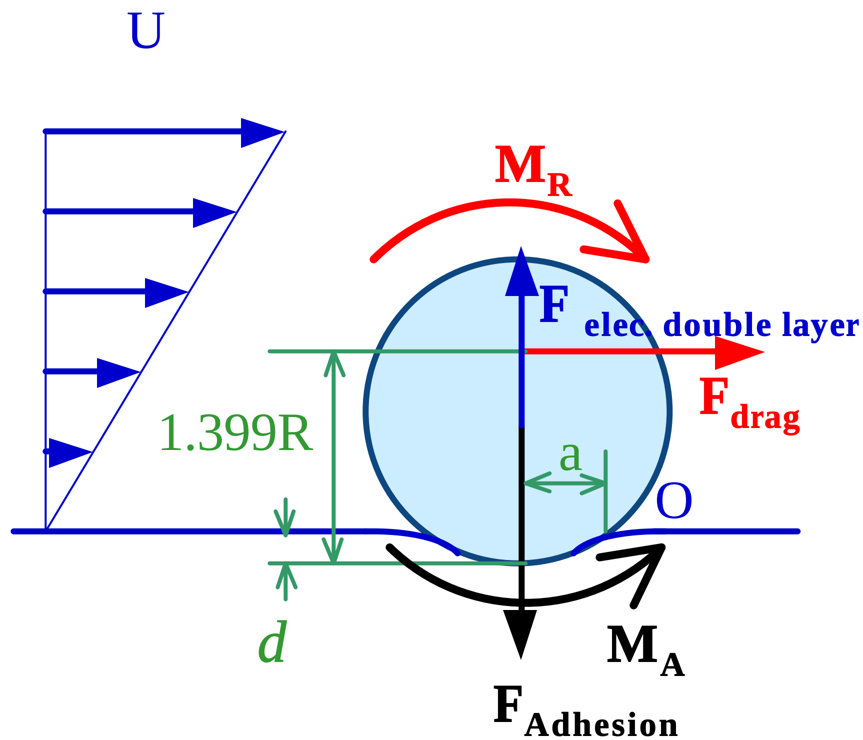
Ratio of Removal/Adhesion Moment (RM)

- RM:

$$RM = \frac{Removal \quad moment}{Adhesion \quad resisting \quad moment}$$

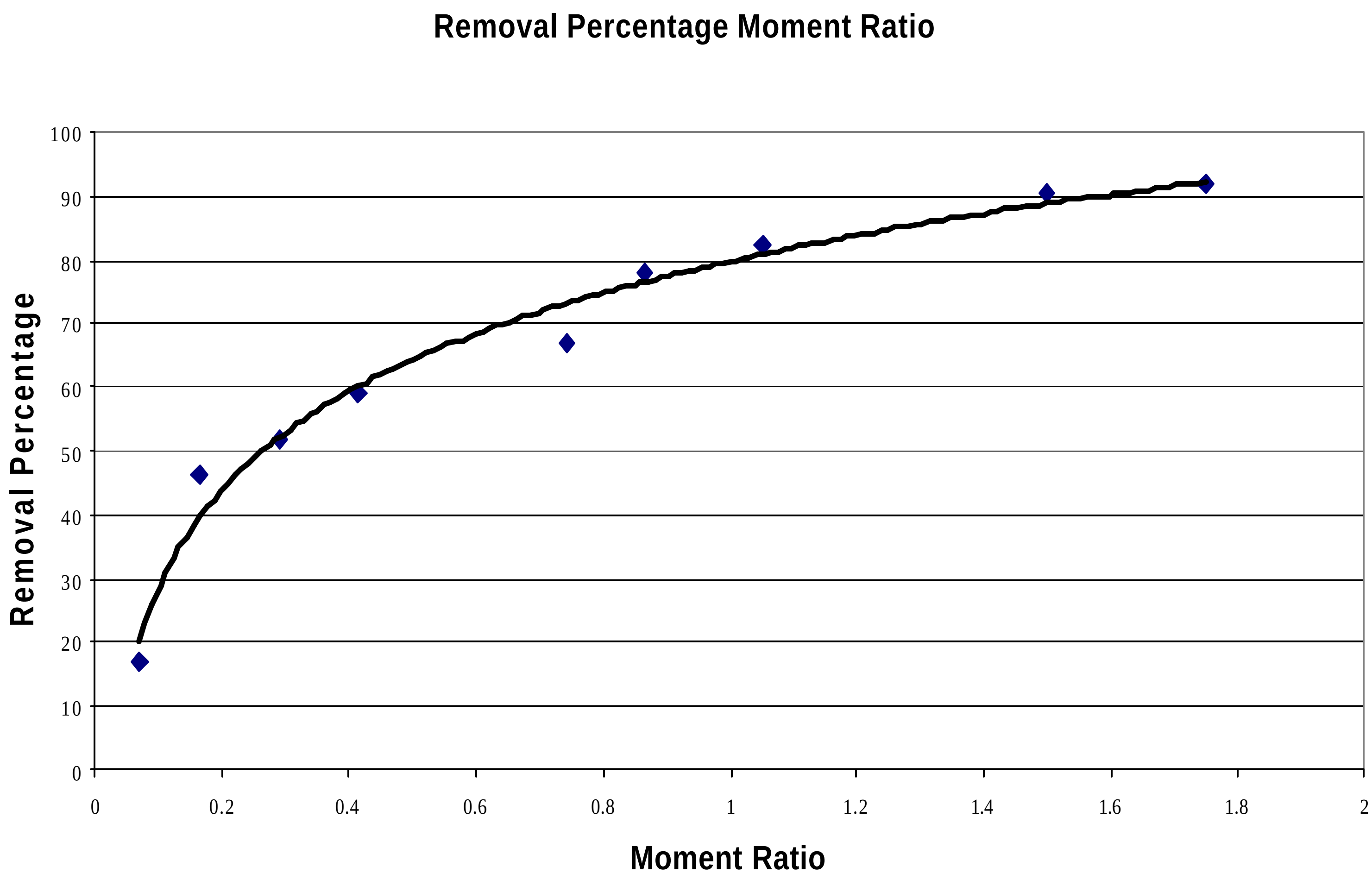
$$RM = \frac{F_d(1.399R - d) + F_{dl} \cdot a}{F_a \cdot a}$$

- When RM >1, most particles are removed.

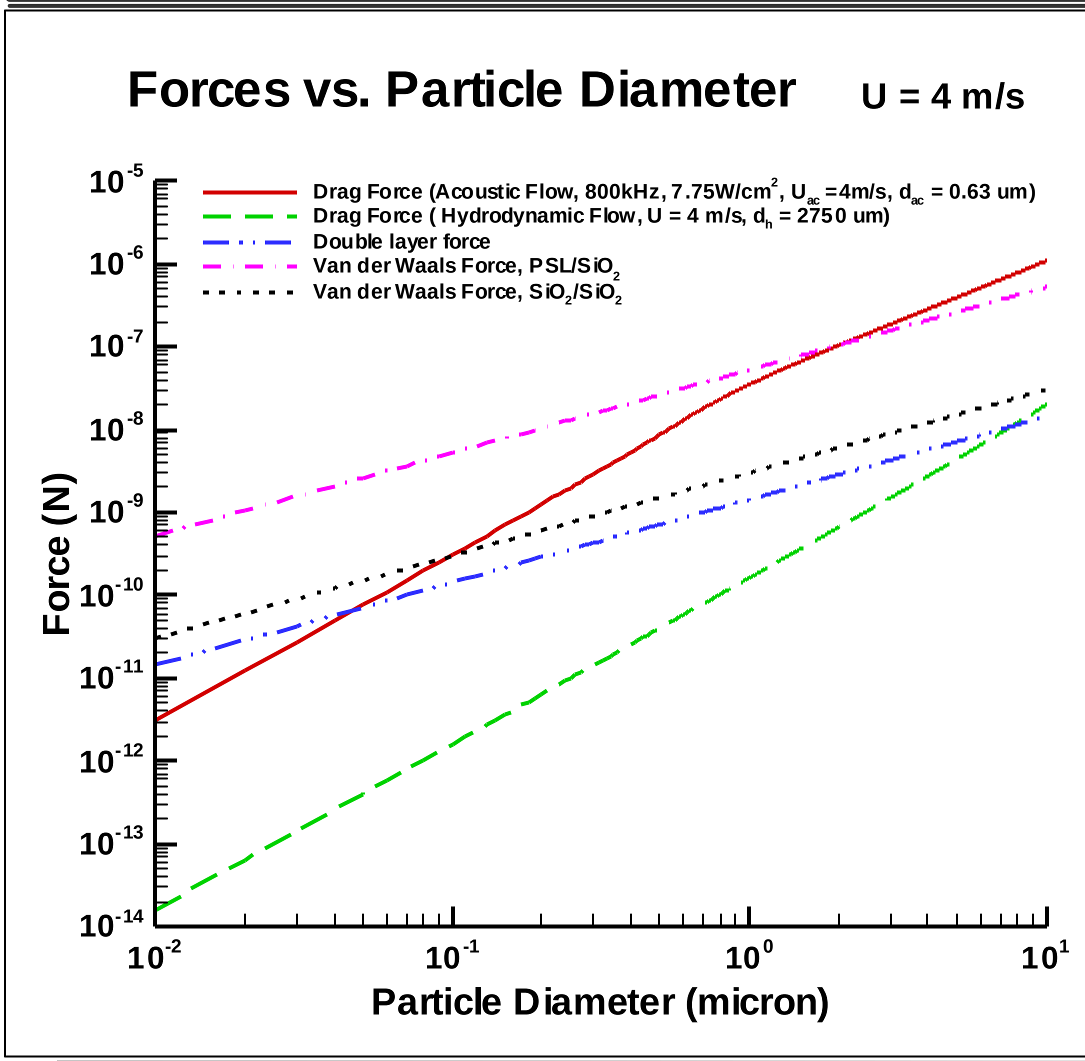


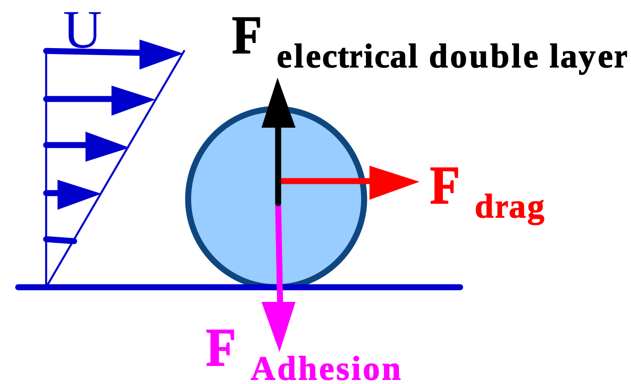
Rolling removal mechanism

Removal Percentage vs. Moment Ratio (Silica Removal Experiment)



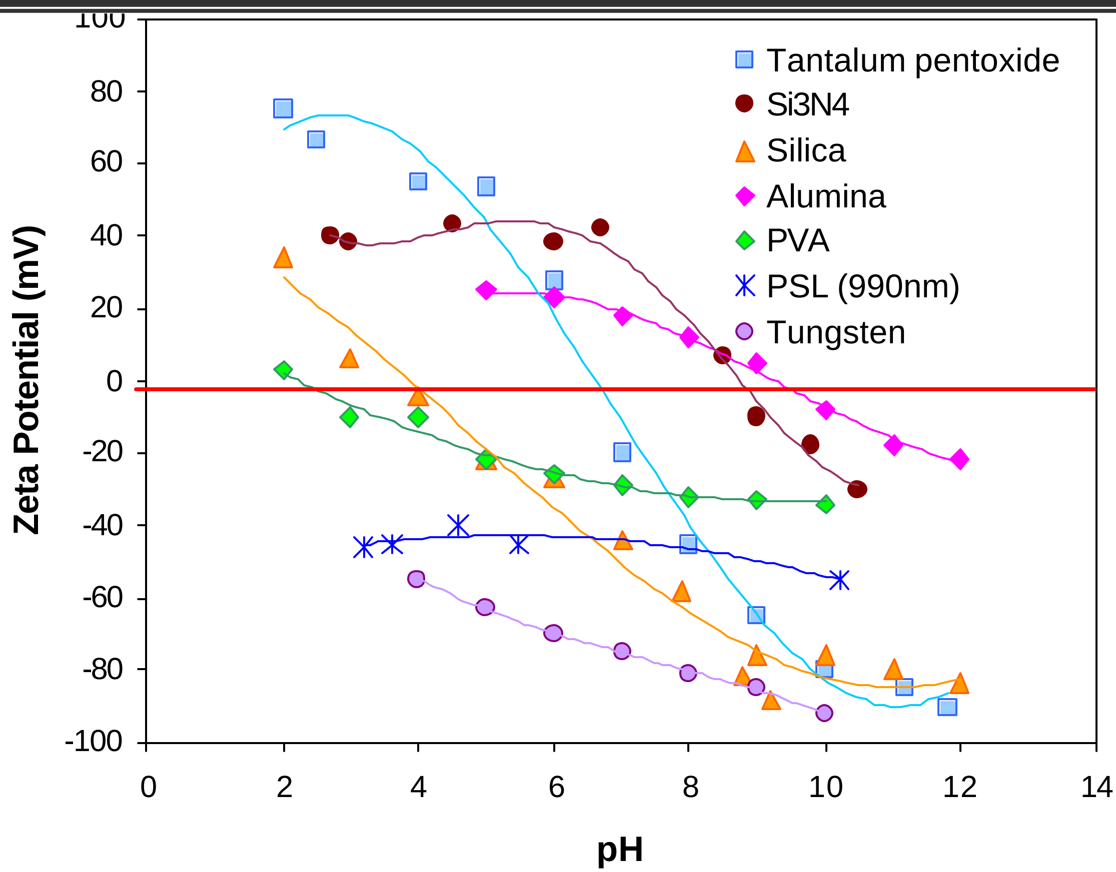
Effect of Particle Size on Adhesion and Removal Forces





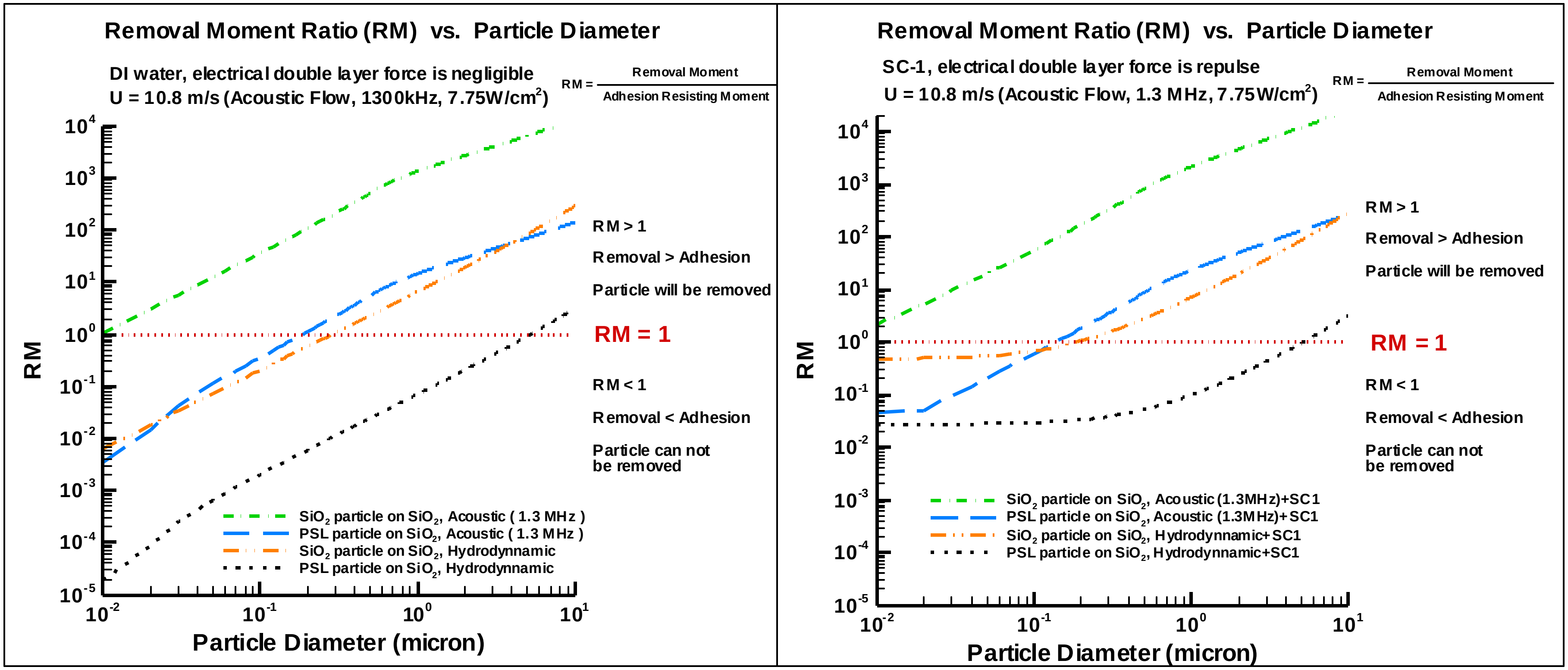
- Drag force, electrical double layer force, and adhesion force all increase with particle size.
- Acting as removal forces,
  - d>100nm, acoustic flow drag force is dominated;
  - 30nm<d<100nm, drag force and electrical double layer force are on same level;
  - d<30nm, electrical double layer force is dominated;

Electrical Double Layer Force



- **At the pH of water, silica, PSL, PVA, and W particles are all negatively charged.**
- **The high negative zeta potentials are measured at high pH solution for SiO_2, Si_3N_4, Al_2O_3, tantalum pentoxide, tungsten, polyvinyl alcohol (PVA), and also for Si and PSL.**
- **Using a high pH cleaning solution, electrical double layer force occurs as a strong repulsion between the particle and the substrate.**

Removal/Adhesion Moment Ratio (RM)

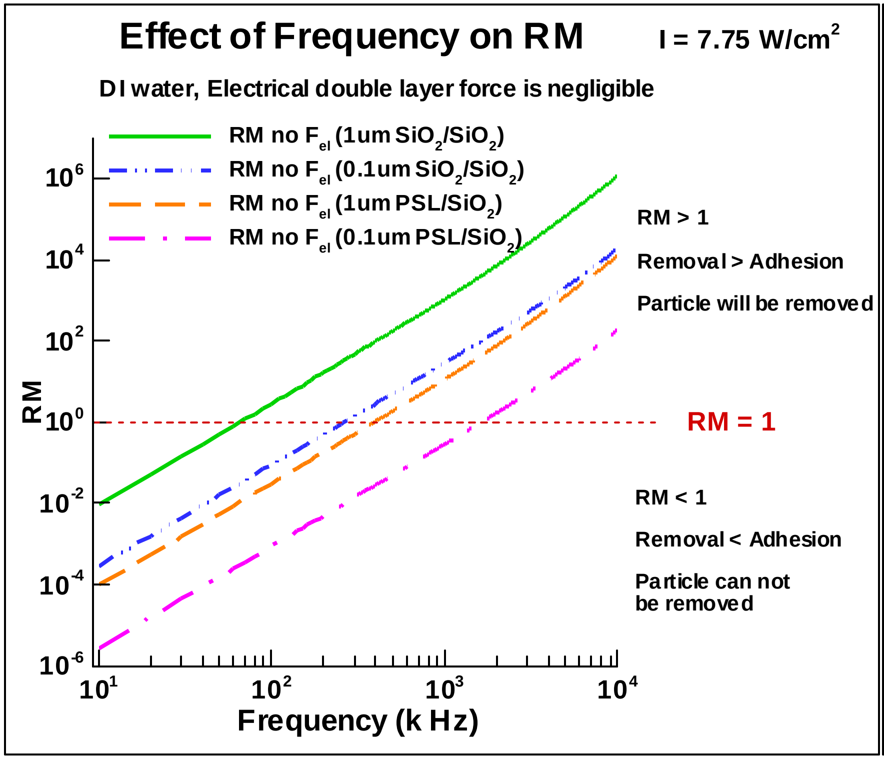


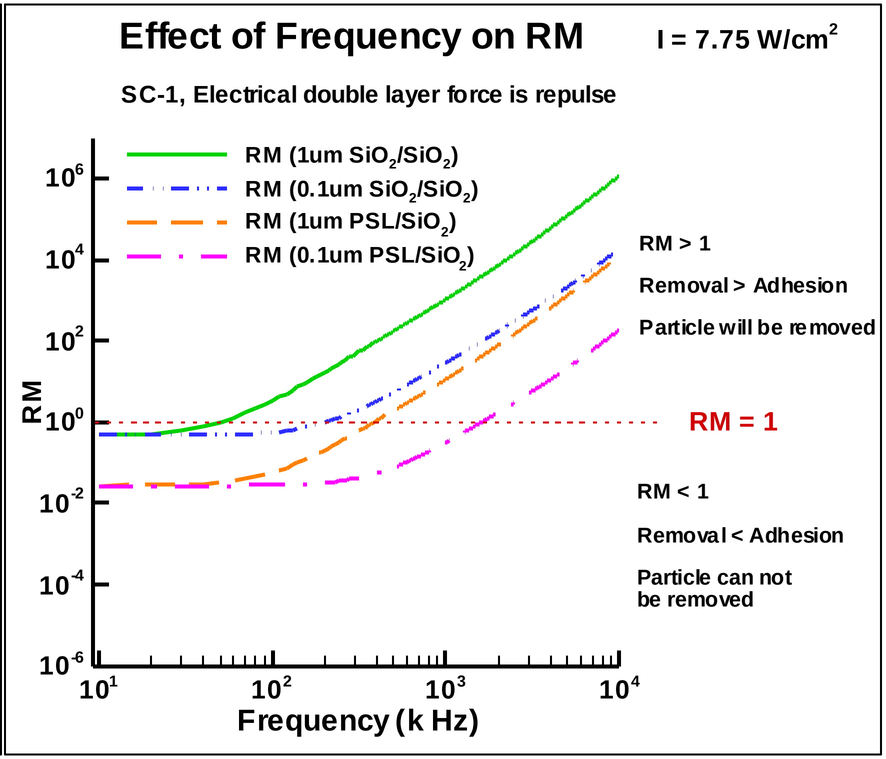
- ❑ **Using DI water only, the removal of nano-size particles (10-100 nm) can be best accomplished using acoustic streaming at frequencies larger than 1.3 MHz.**

Effects of Frequency on RM

DI water, Electrical double layer force is negligible

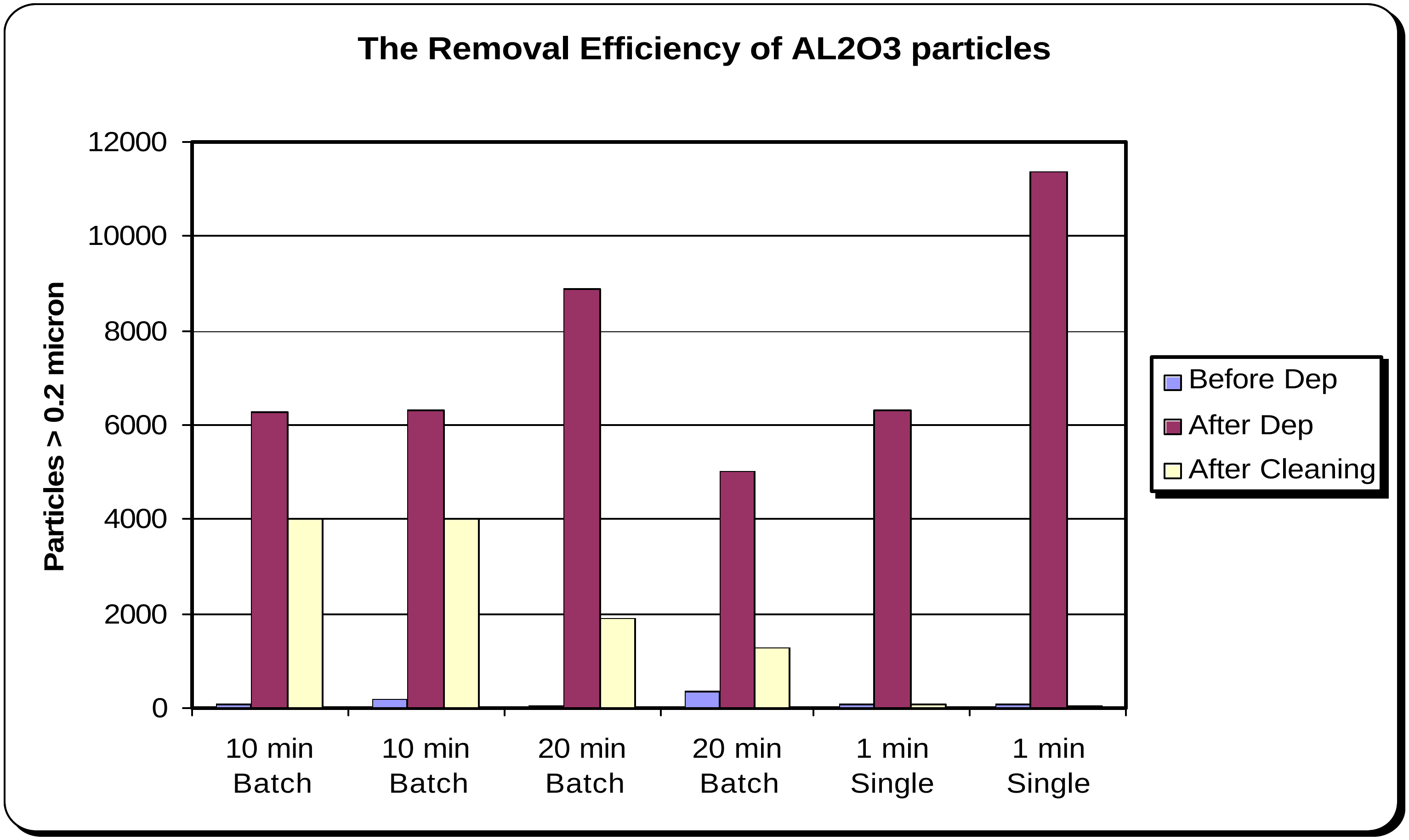
SC-1, Electrical double layer force is repulsive force



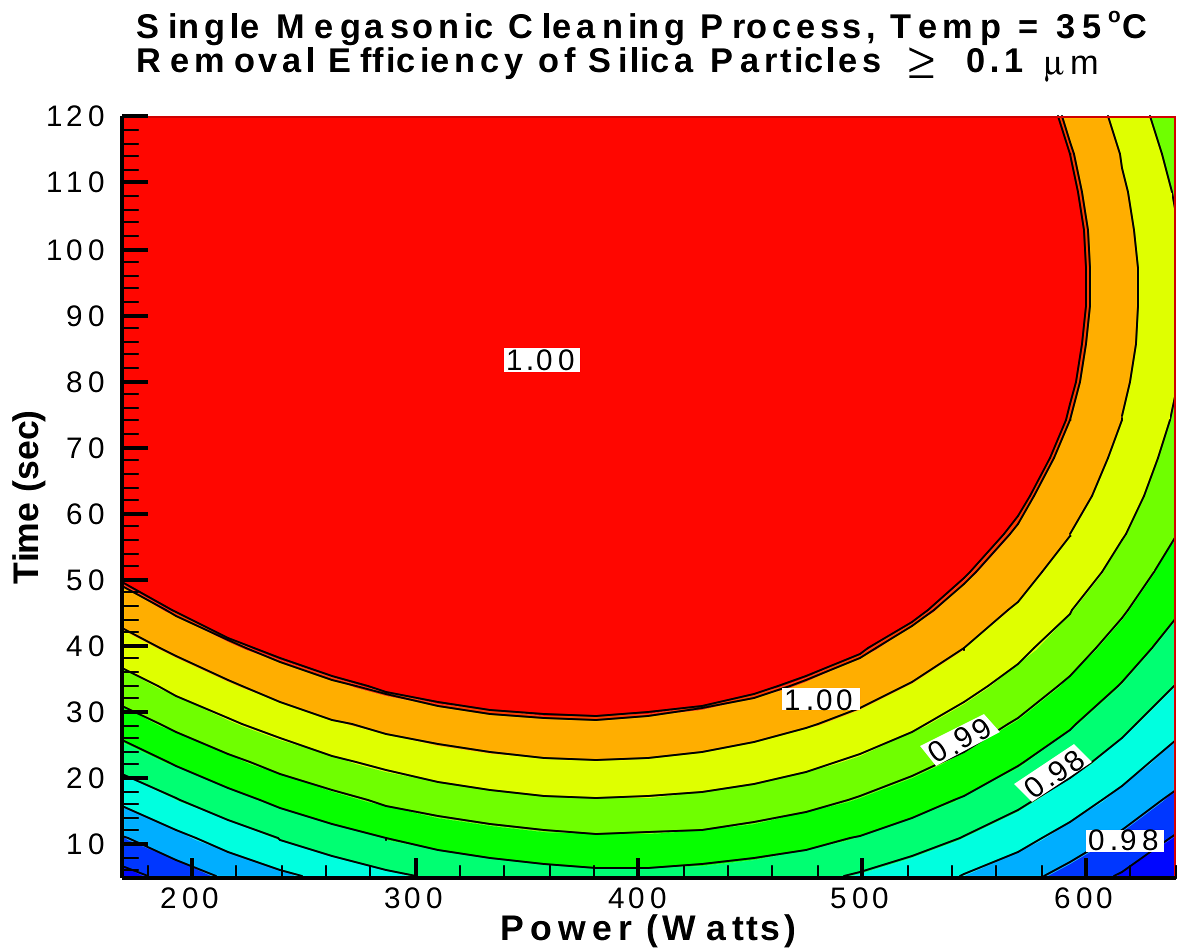


- **The smaller the particles, the higher frequency acoustic flow is needed.**
- **Soft particles (PSL) are more difficult to remove than hard particle (silica), needing almost an order of magnitude higher frequency.**

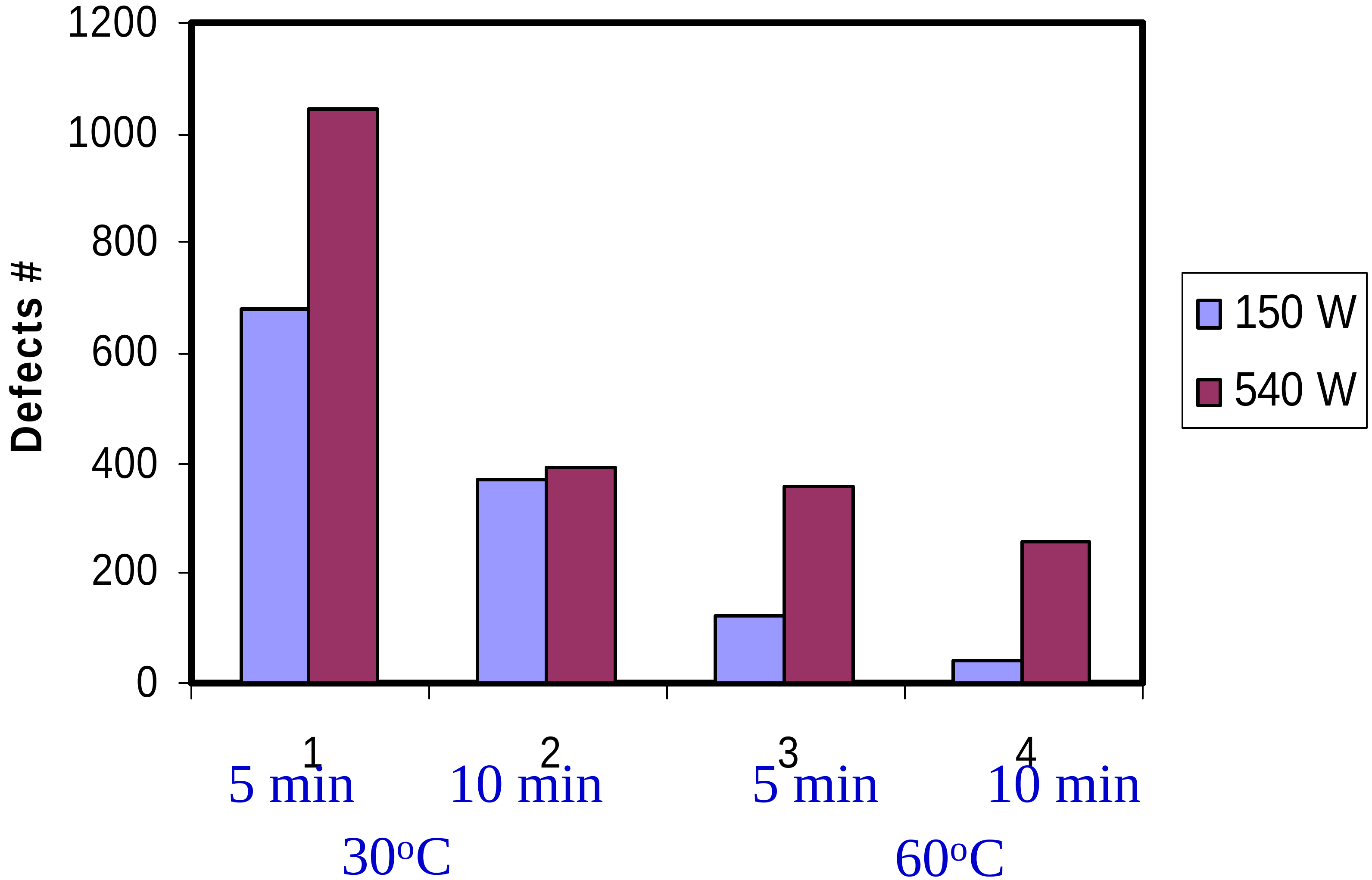
Fast Single Wafer Post-CMP Cleaning
Single versus Batch



- Complete removal of silica particles down to 100nm is achievable by using a single wafer megasonic cleaning with DI water only.



Megasonic Cleaning of Polished TOX Wafers Using SC1



Key Results from Preliminary Research

- **Megasonics induced acoustic streaming is essential to the removal of submicron and nano-size particles.**
- **As the frequency increases, the acoustic boundary layer thickness decreases and streaming velocity increases thereby increasing the removal (drag) force.**
- **Using DI water, the removal of nano-size particles (10-100 nm) can be best accomplished using acoustic streaming at frequencies larger than 1.3 MHz.**
- **Utilizing the electrical double layer force as a repulse force, by using basic chemistry, removal of 10nm silica particle can be accomplished using megasonic cleaning above 800 kHz.**
- **Acting as removal forces,**
  - d>100nm, acoustic flow drag force is dominated;
  - 30nm<d<100nm, drag force and electrical double layer force are on same level;
  - d<30nm, electrical double layer force is dominated;
- **Soft particles (such as Polystyrene Latex PSL) are more difficult to remove than hard particle (silica), because of adhesion induced deformation, needing almost an order of magnitude higher frequency.**