Effect of kinematics and abrasive particle dynamics on material removal rate uniformity during polishing

Armin Saeedi Vahdat[1,2] and S V Babu[2]

[1]Dept. of Mechanical and Aeronautical Engineering

[2]Center for Advanced Material Processing (CAMP)

Clarkson University

Potsdam, New York 13699-5725

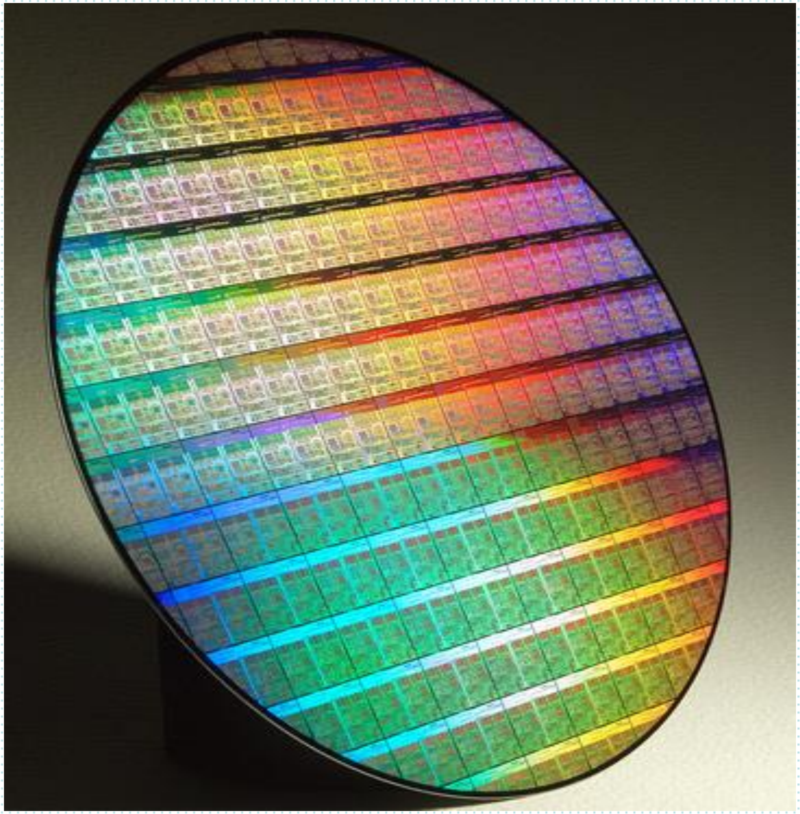
April16, 2015

Motivation and Objective

Clarkson UNIVERSITY

Scaling down the structures and increasing wafer size ⇨ MRR uniformity becomes more challenging

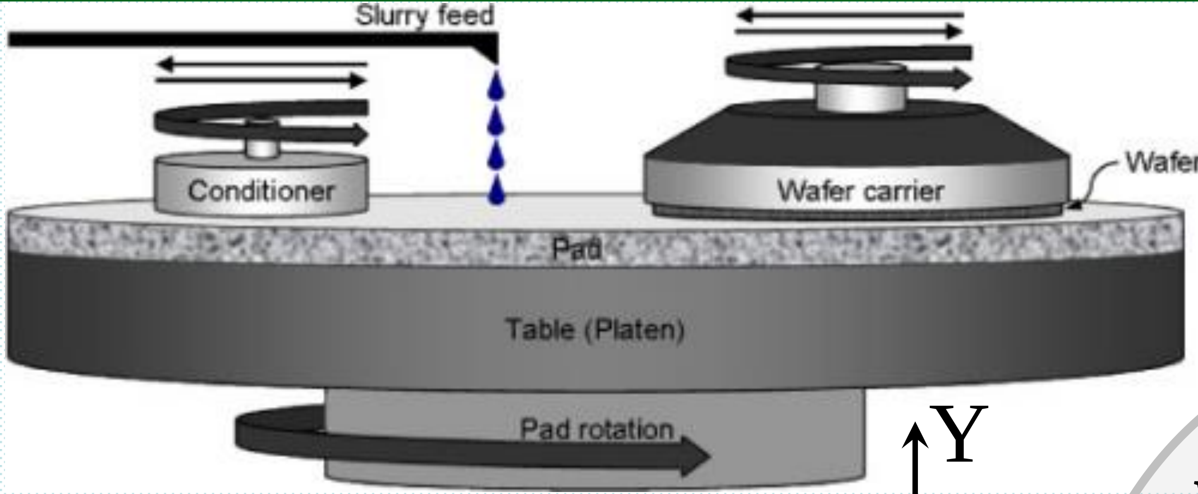
⇩

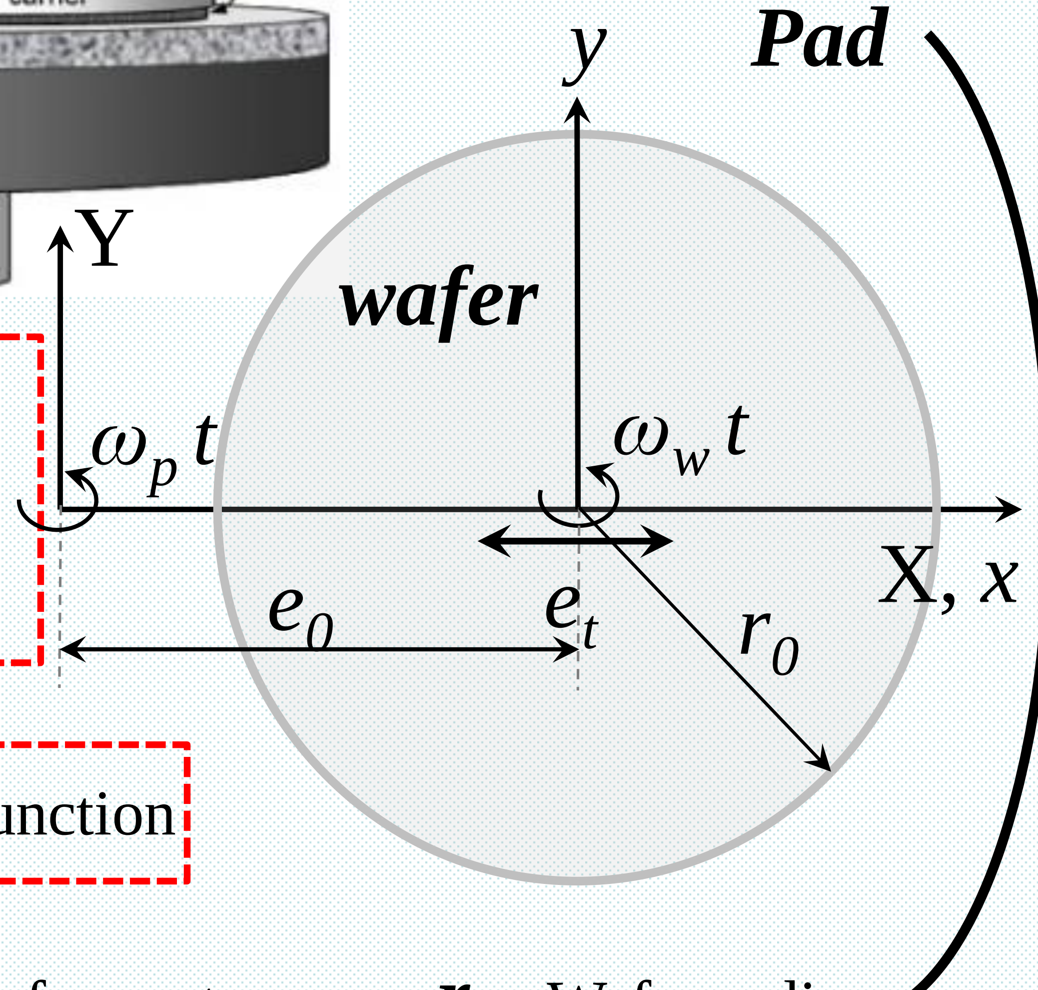


CMP kinematics based on slurry distribution and particle trajectories have a big impact on MRR profiles.

(Pressure and temperature profiles are also very important)

Chemical Mechanical Polishing Kinematics





$\boldsymbol{\omega_p}$: Platen rotational/angular velocity

$\boldsymbol{\omega_w}$: wafer rotational/angular velocity

Rotary Dynamics

$\boldsymbol{e_t}$: Carrier oscillatory motion function

Reciprocation Dynamics

$\boldsymbol{e_0}$: Distance between pad and wafer centers, $\boldsymbol{r_0}$: Wafer radius

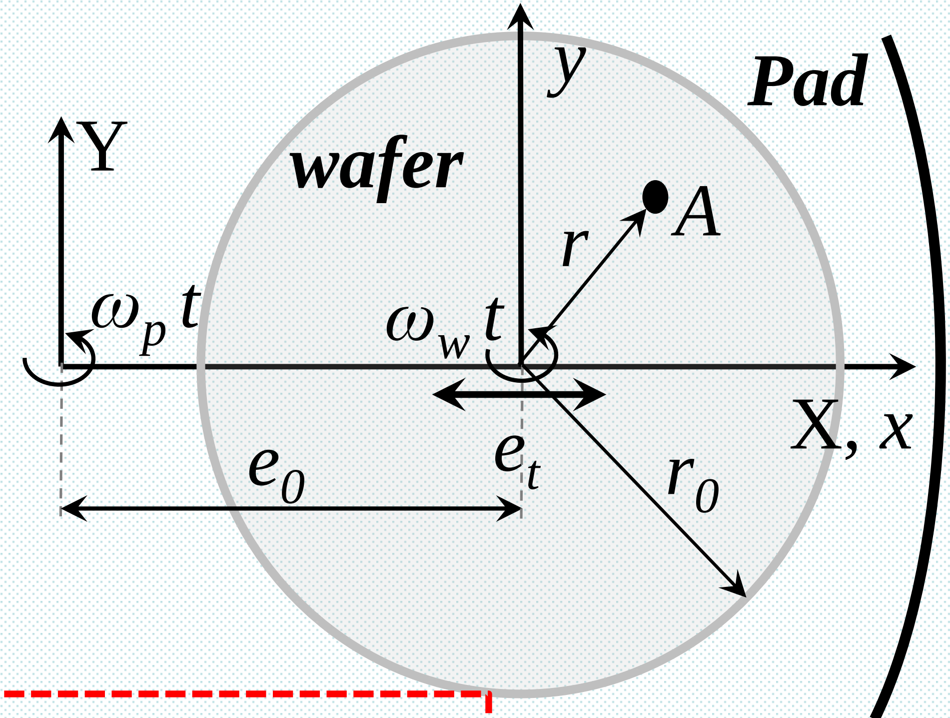
Velocity Field on Wafer Surface

Relative velocity of a point on the wafer:

$$\vec{v}_A = \vec{\omega}_p \times (\vec{e}_0 + \vec{e}_t + \vec{r}) - \vec{\omega}_p \times \vec{r} - \dot{\vec{e}}_t$$

$$v_A = \omega_p e_0 \sqrt{\left(\dot{e}_t / (\omega_p e_0) + y(1-\alpha)/e_0\right)^2 + \left(1 + e_t/e_0 + x(1-\alpha)/e_0\right)^2}$$

where $\alpha = \omega_w / \omega_p$



For typical rotary-type polishers:

$$\dot{e}_t << \omega_p e_0,\ e_t << e_0$$

⇩

$$v_A \cong \omega_p e_0 \sqrt{\left(y(1-\alpha)/e_0\right)^2 + \left(1 + x(1-\alpha)/e_0\right)^2}$$

Velocity Field on Wafer Surface

When $\boldsymbol{\alpha} = \mathbf{1}$ $(\omega_p = \omega_w)$

$$v_A \cong \omega_p e_0 \sqrt{\left(y\underbrace{(1-\alpha)}_{=0}/e_0\right)^2 + \left(1 + x\underbrace{(1-\alpha)}_{=0}/e_0\right)^2} \Rightarrow v_A \cong \omega_p e_0$$

Uniform velocity field all over the wafer

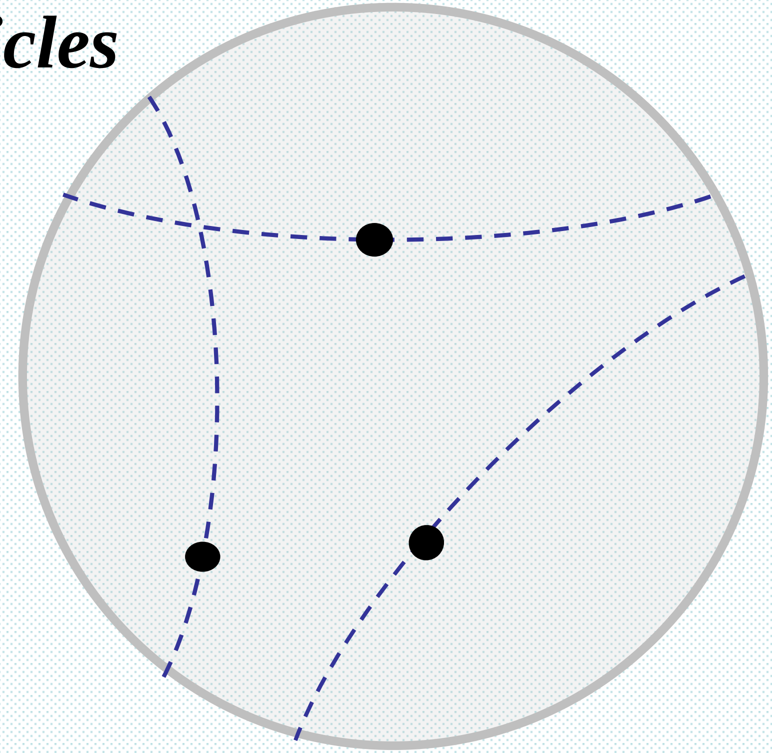
Assuming uniform pressure distribution, **Preston's** equation suggests uniform MRR:

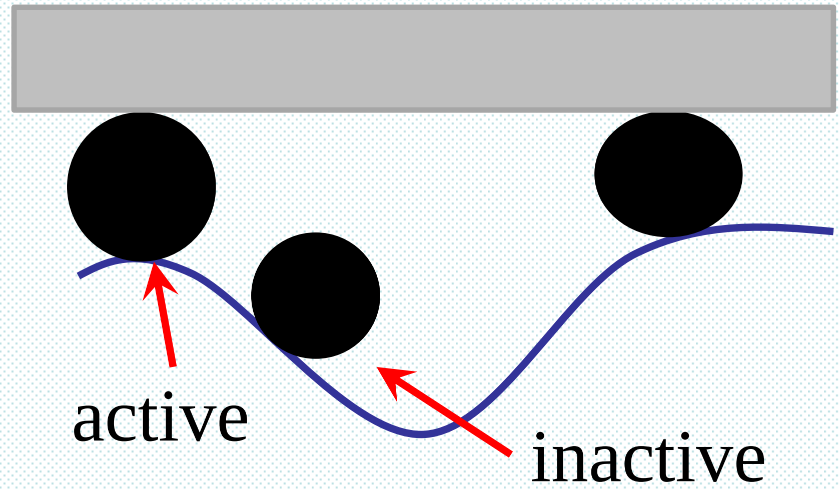
$$MRR(\mathrm{x},\mathrm{y}) = k_p v_A(\mathrm{x},\mathrm{y})\, p(\mathrm{x},\mathrm{y}) \Rightarrow MRR(\mathrm{x},\mathrm{y}) = k_p\, p\, \omega_p e_0 = cont.$$

However experimental results suggests $\boldsymbol{\alpha} = \mathbf{1}$ is not a proper velocity ratio option in order to get uniform MRR profile.

Particle Trajectories and MRR

Particles trapped between pad asperities and wafer are ***active particles***





Non active abrasives cause zero/negligible MRR

MRR uniformity depends on:

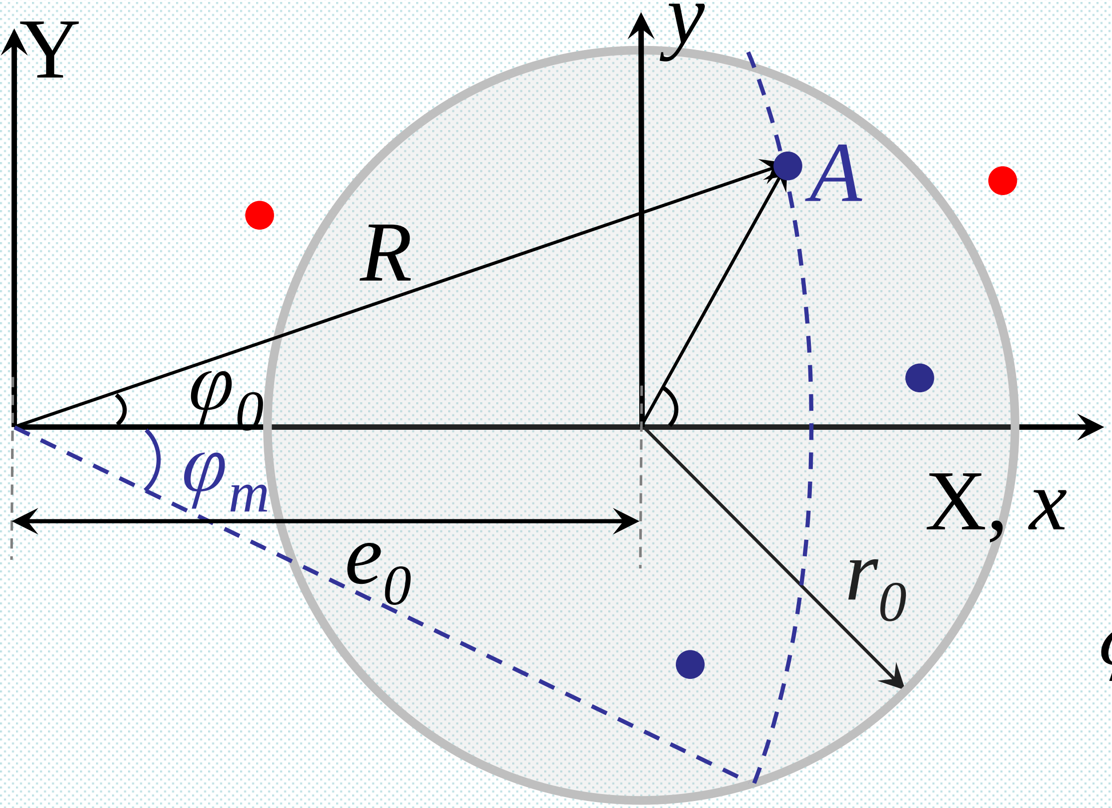
Active particles trajectories distribution + Material removed along each trajectory (particle size)

Description of a Particle Location

Initial location of each active particle of pad:

$$\begin{bmatrix} X_A \\ Y_A \end{bmatrix} = R \begin{bmatrix} \cos\varphi_0 \\ \sin\varphi_0 \end{bmatrix}$$

Location of all Active particles participating in MRR on wafer follows these conditions



$$|R - e_0| \le r_0$$

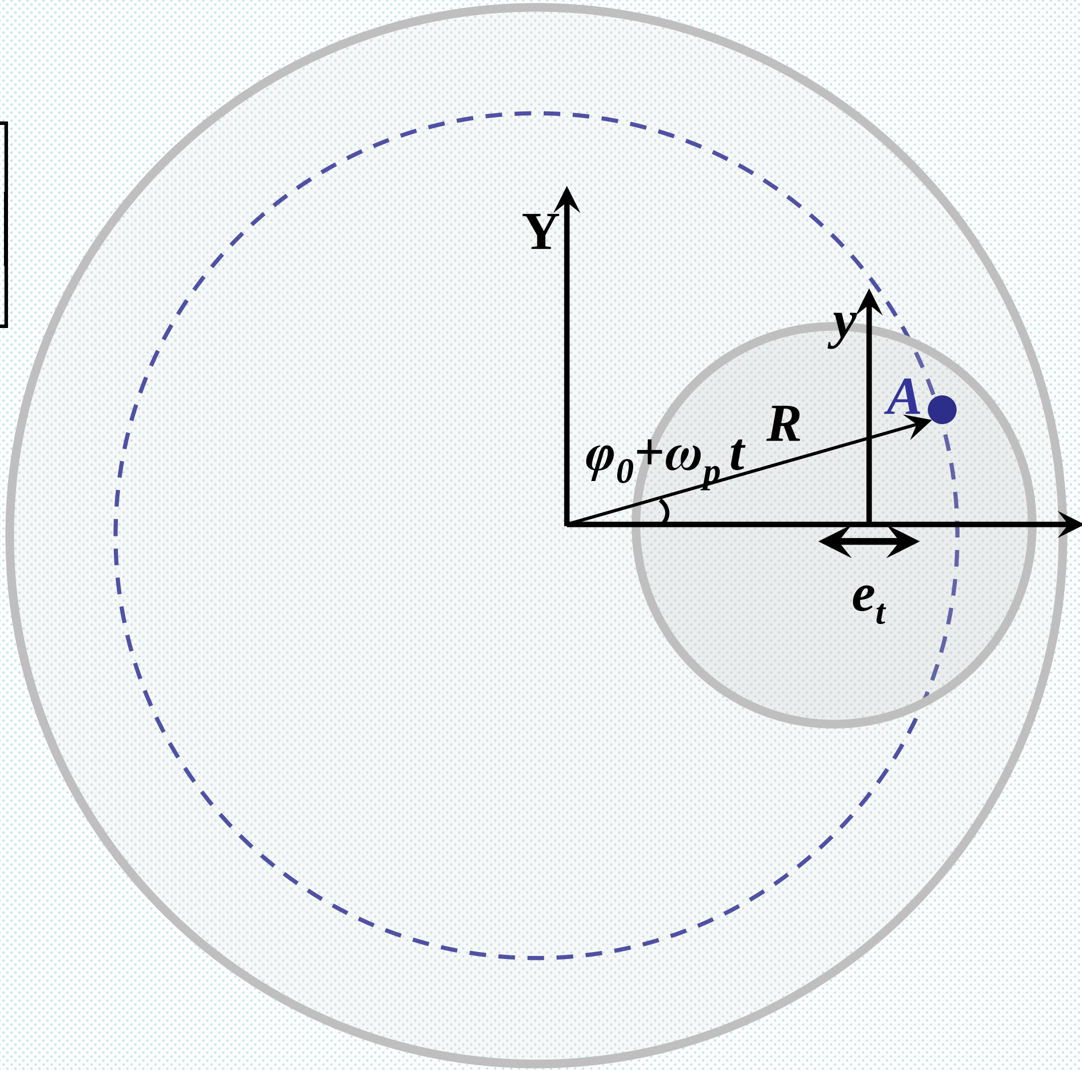
$$-\varphi_m \le \varphi_0 \le \varphi_m$$

$$\varphi_m = \cos^{-1}\left(\frac{R^2 + e_0^2 - r_0^2}{2 R e_0}\right)$$

Description of a Particle Trajectory

Time dependent trajectory of a particle in ***fixed/global*** coordinate:

$$\begin{bmatrix} X_A(t) \\ Y_A(t) \end{bmatrix} = R \begin{bmatrix} \cos(\varphi_0 + \omega_p t) \\ \sin(\varphi_0 + \omega_p t) \end{bmatrix}$$

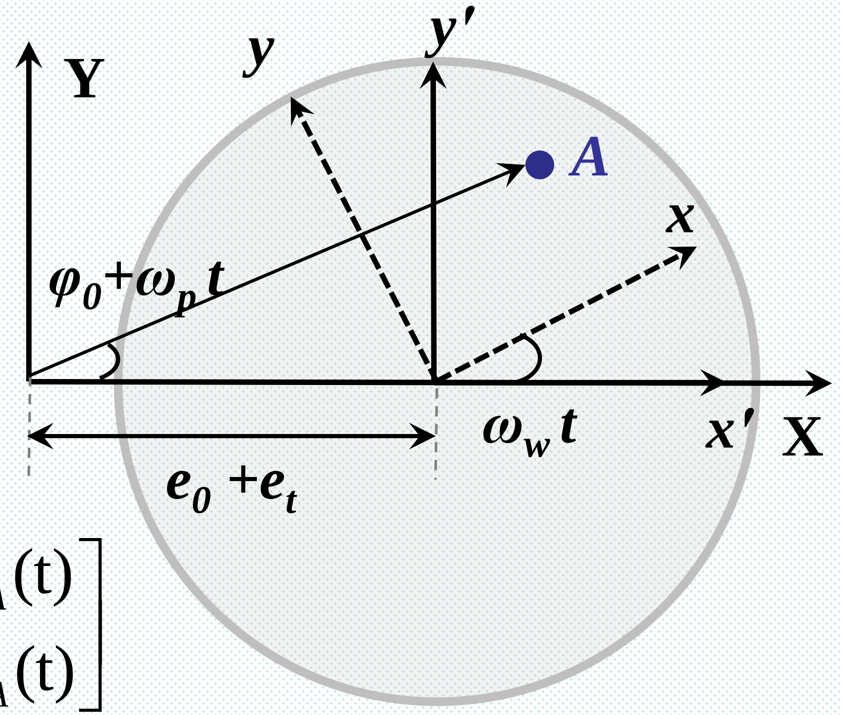


Assumption:

Particle leaves the wafer area and rotates with pad velocity and eventually reenters the wafer area.??

Description of a Particle Trajectory

Time-dependent particle locations in fixed and moving coordinates are related as:



$$\begin{bmatrix} X_A(t) \\ Y_A(t) \end{bmatrix} = \begin{bmatrix} x'_A(t) \\ y'_A(t) \end{bmatrix} \begin{bmatrix} e_0 + e_t \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} x'_A(t) \\ y'_A(t) \end{bmatrix} = \begin{bmatrix} \cos(\alpha\,\omega_p\, t) & -\sin(\alpha\,\omega_p\, t) \\ \sin(\alpha\,\omega_p\, t) & \cos(\alpha\,\omega_p\, t) \end{bmatrix} \begin{bmatrix} x_A(t) \\ y_A(t) \end{bmatrix}$$

Carrier oscillatory motion is described using its amplitude and frequency:

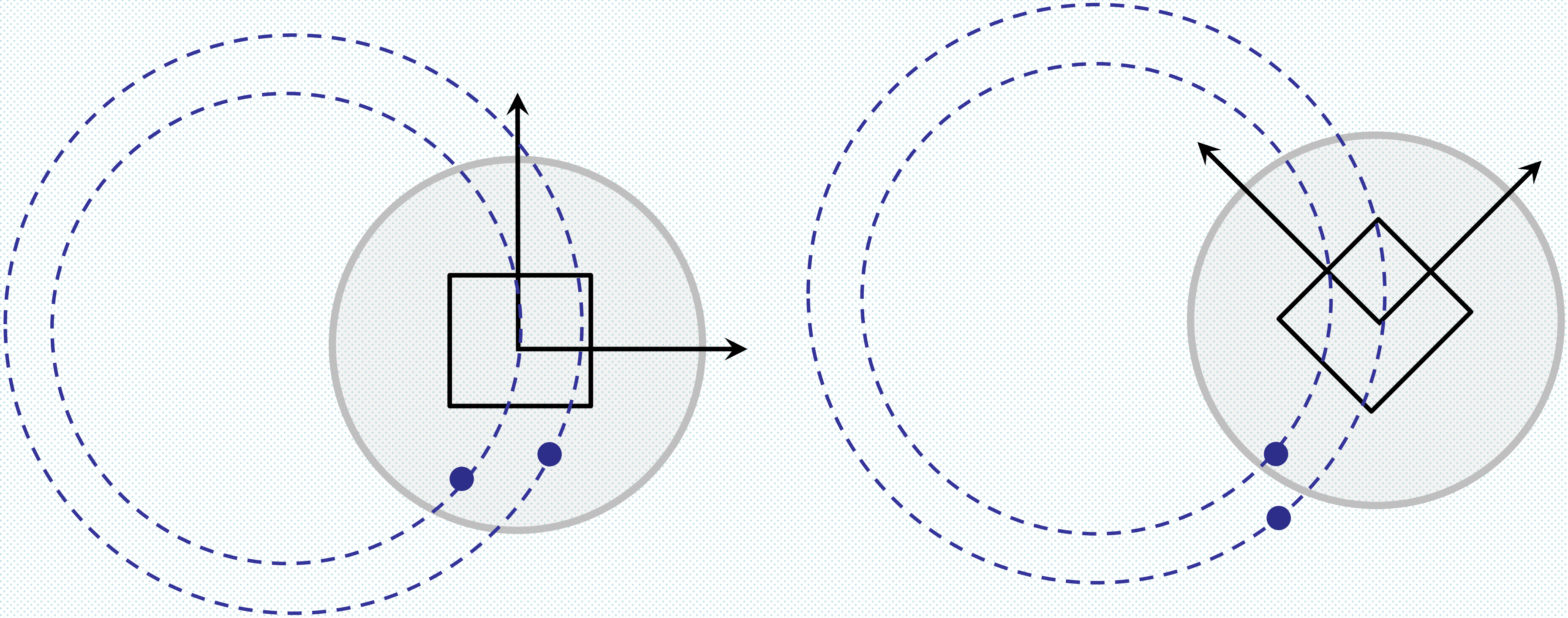
$$e_t = A_e \sin(\omega_e t)$$

Zhao, Dewen, et al. "Kinematic optimization for chemical mechanical polishing based on statistical analysis of particle trajectories." *Semiconductor Manufacturing, IEEE Transactions on* 26.4 (2013): 556-563.

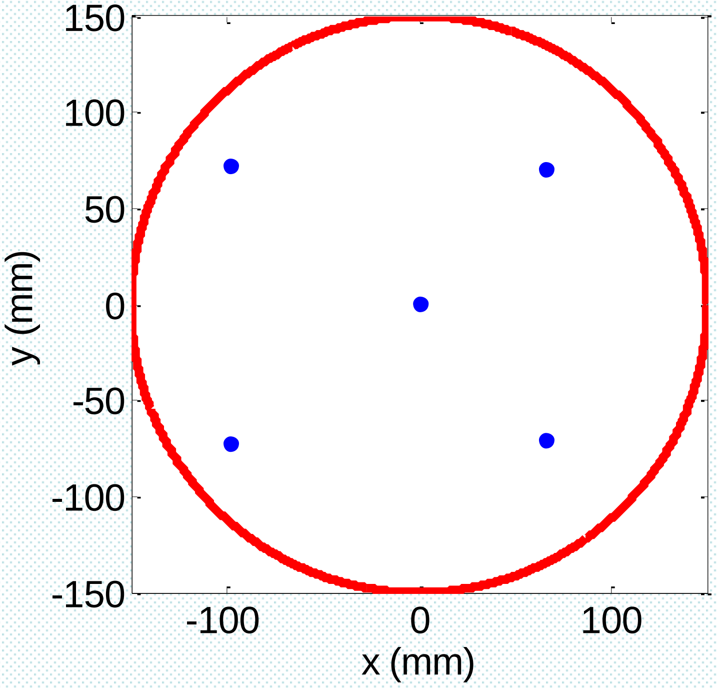
Description of a Particle Trajectory

Time dependent trajectory of a particle in local coordinate system can be expressed:

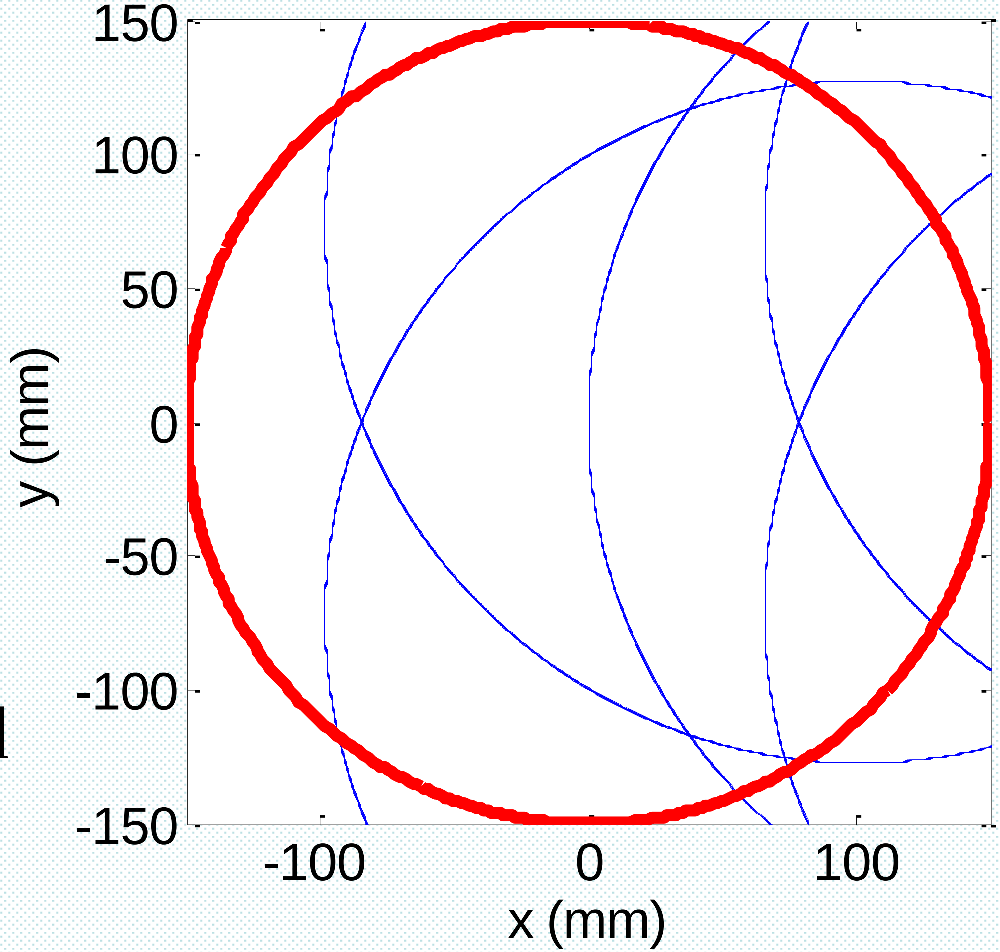
$$\begin{bmatrix} x_A(\mathrm{t}) \\ y_A(\mathrm{t}) \end{bmatrix} = \begin{bmatrix} \cos(\alpha\,\omega_p\,\mathrm{t}) & \sin(\alpha\,\omega_p\,\mathrm{t}) \\ -\sin(\alpha\,\omega_p\,\mathrm{t}) & \cos(\alpha\,\omega_p\,\mathrm{t}) \end{bmatrix} \begin{bmatrix} R\cos(\varphi_0+\omega_p\,\mathrm{t})-(e_0+A_e\sin(\omega_e t)) \\ R\sin(\varphi_0+\omega_p\,\mathrm{t}) \end{bmatrix}$$



Five Particle Trajectories (No Oscillation)

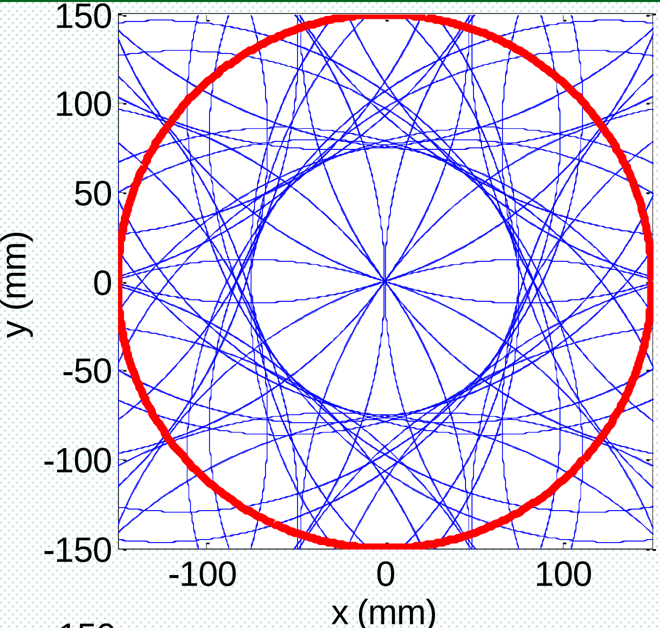


When $\boldsymbol{\alpha} = \mathbf{1}$ ($\omega_p = \omega_w$)

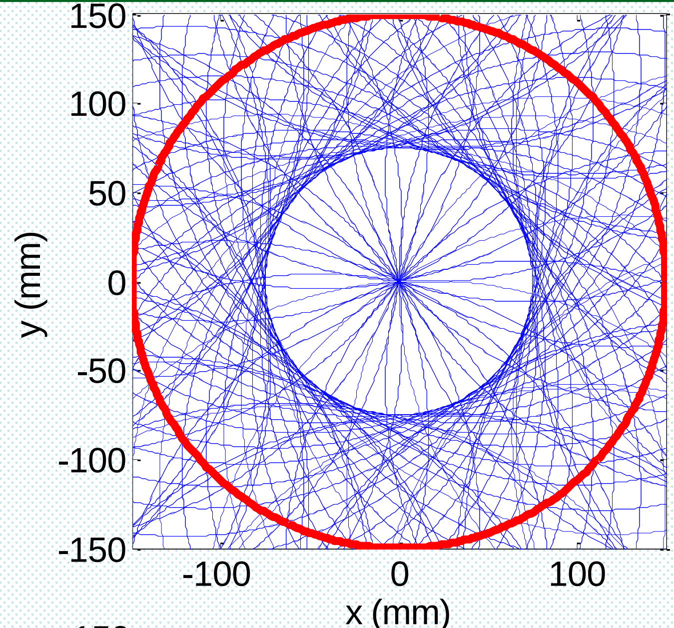


Five particles are located on pad asperities

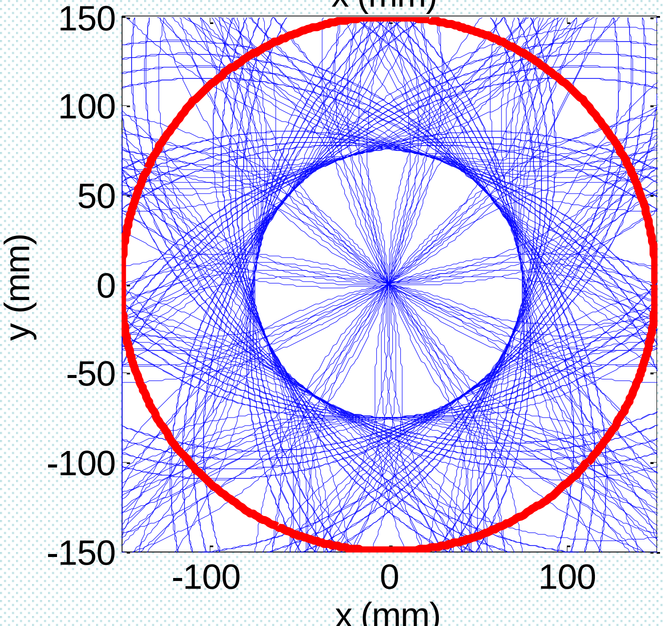
Five Particle Trajectories (No Oscillation)



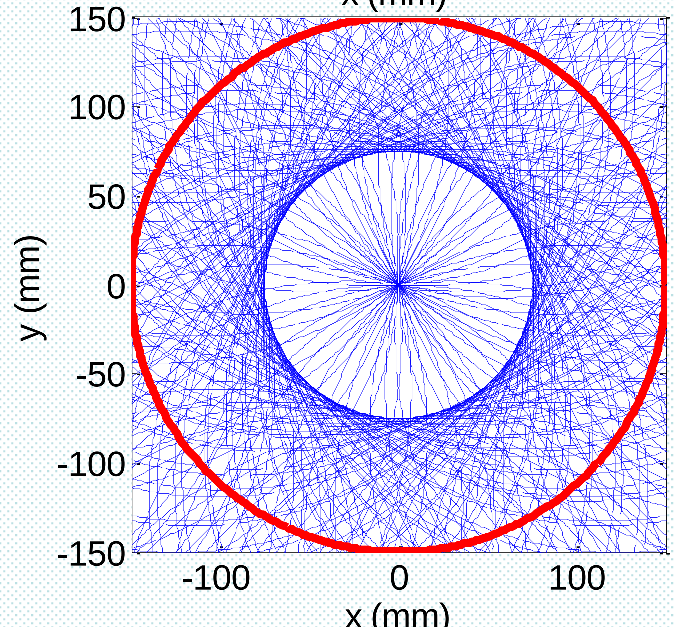
α=0.90



α=0.92

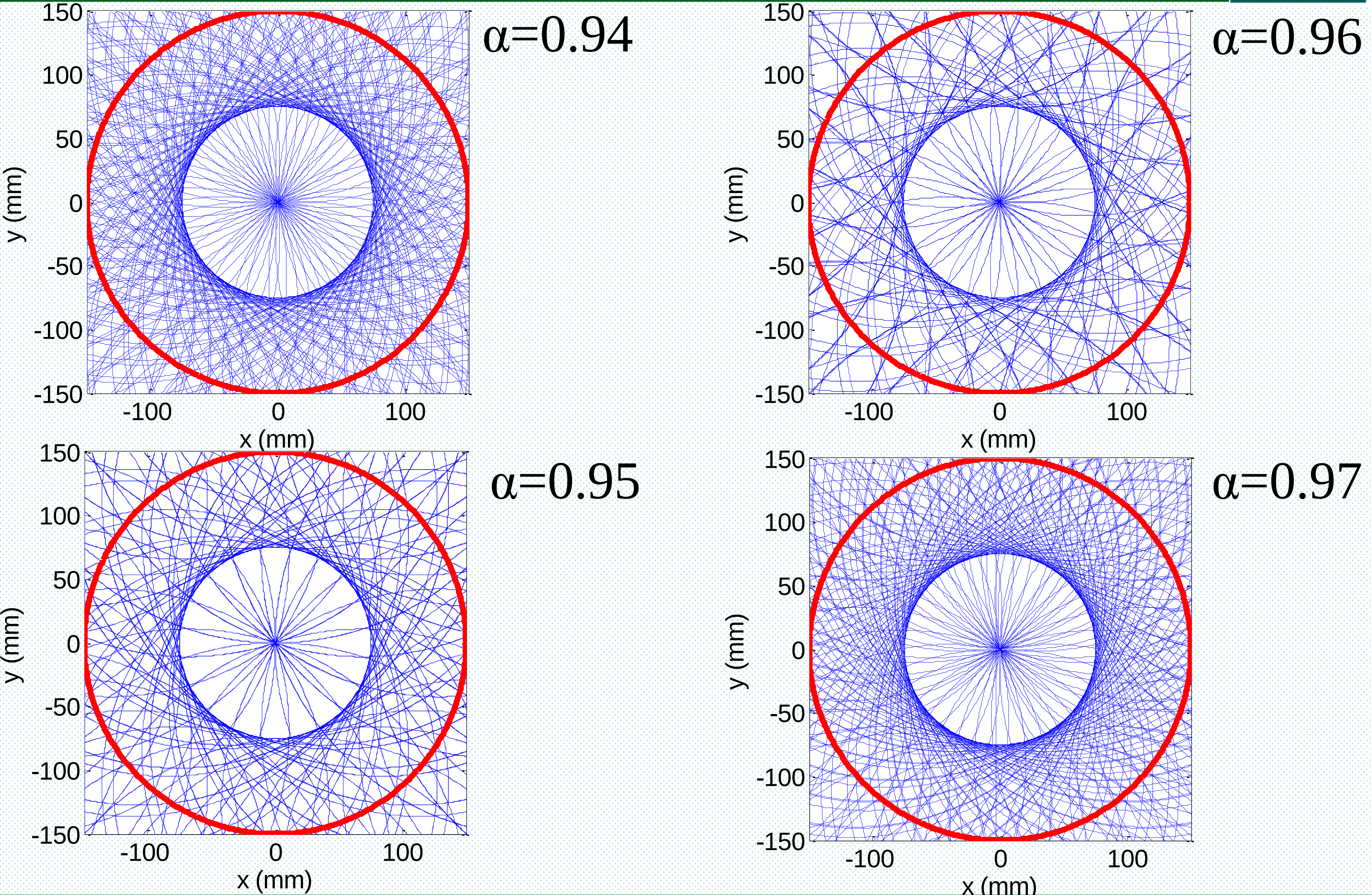


α=0.91

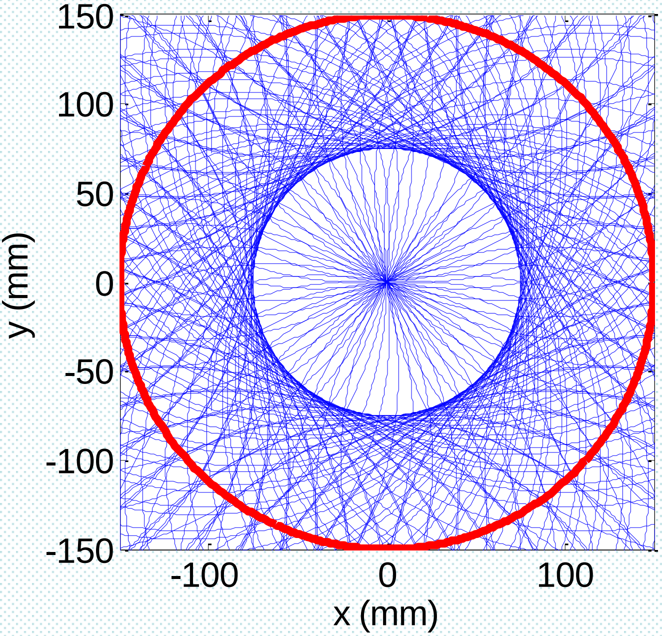


α=0.93

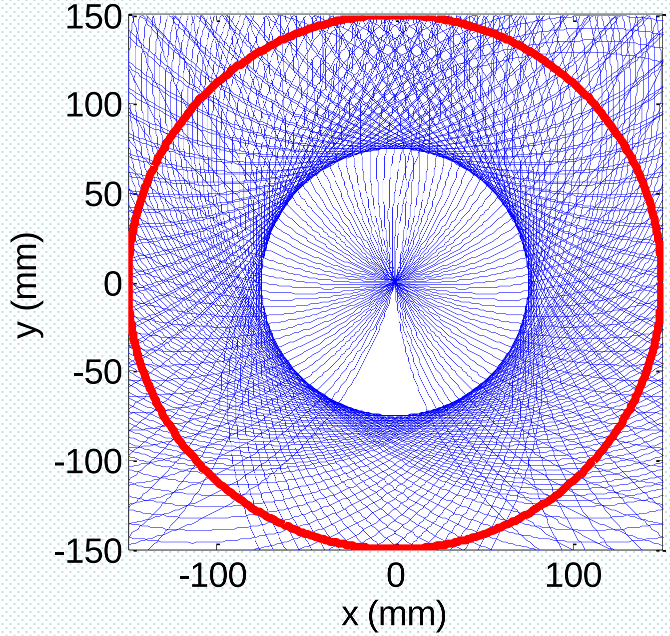
Five Particle Trajectories (No Oscillation)



Five Particle Trajectories (No Oscillation)



α=0.98

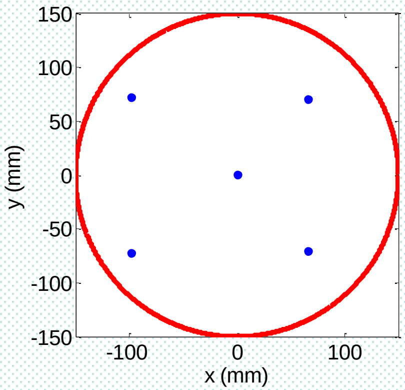


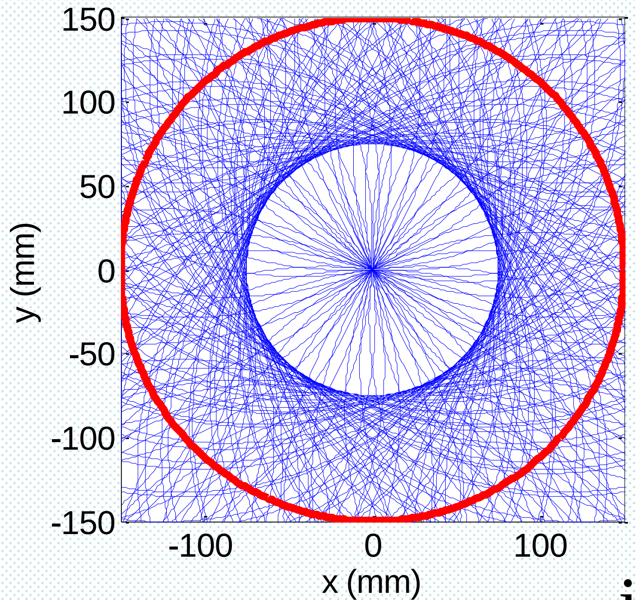
α=0.99

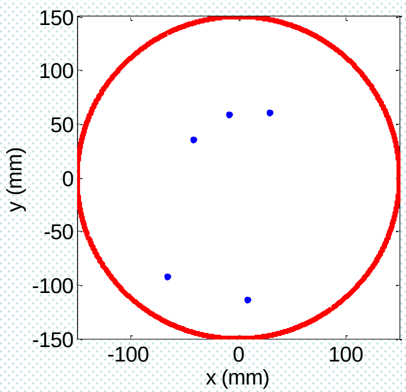
For α=0.91, 0.93,0.94,0.97 the trajectories are better distributed all over the wafer surface.

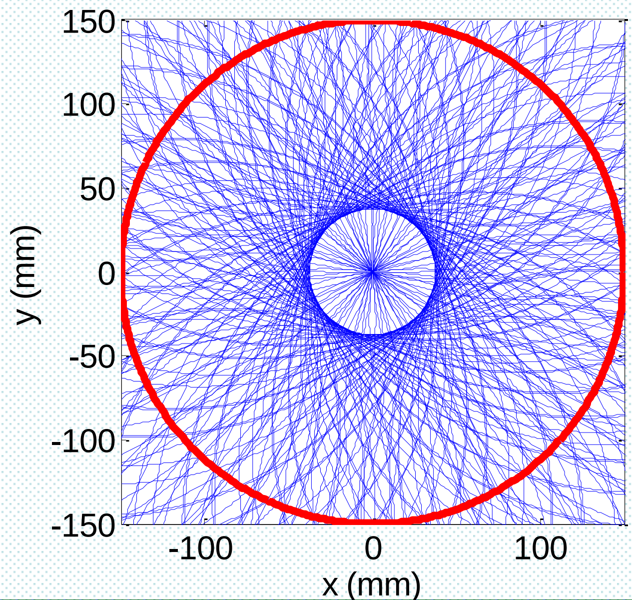
A ring with lower trajectory density is observed.

Five Particle Trajectories (No Oscillation)







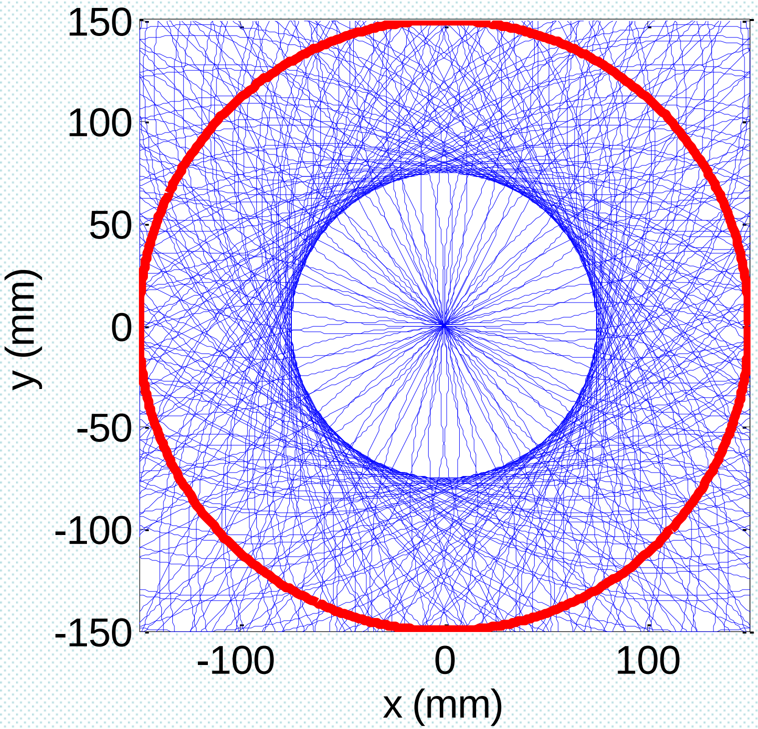


The observed ring is an ***artifact*** which is induced due to the initial ***particle locations***

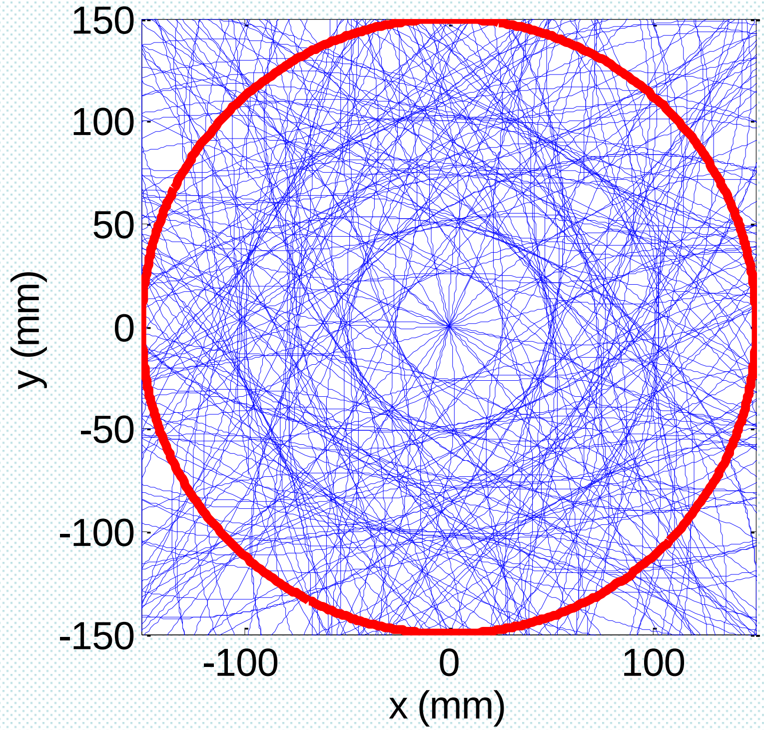
Five Particle Trajectories

The trajectory distribution density at the center of the wafer can be improved by making the carrier oscillate

No oscillation

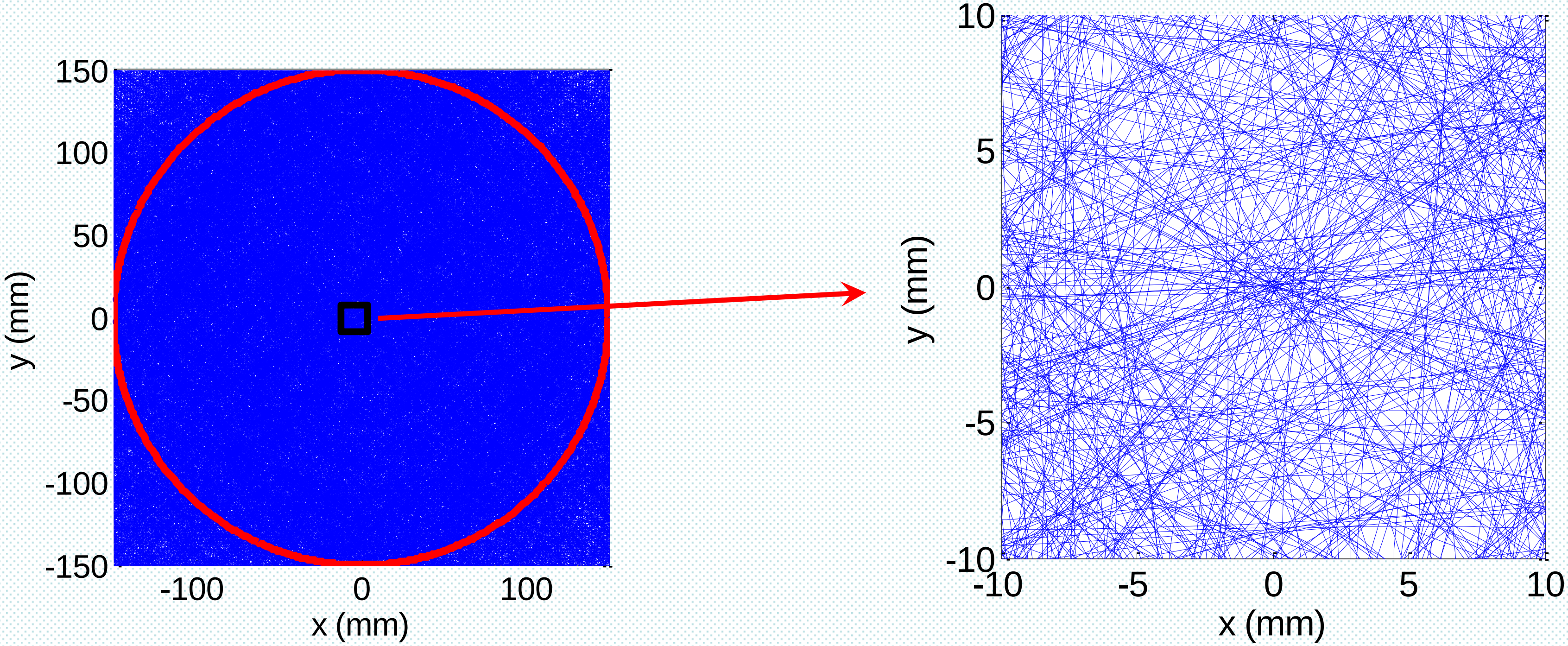


With Oscillation



100 Particle Trajectories

When number of particles increase, the trajectory distribution appears uniform but it is not.

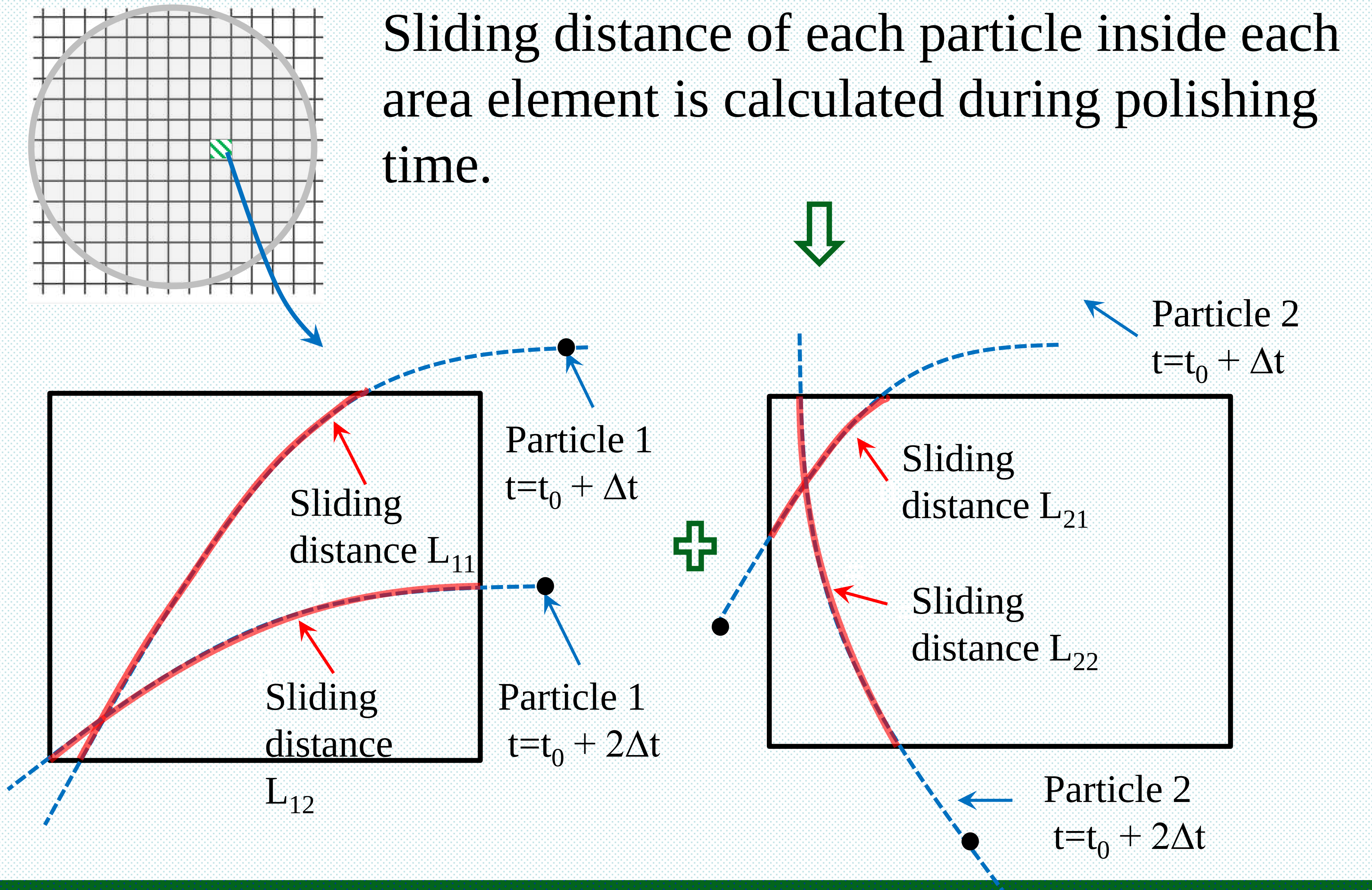


Therefore a quantitative technique is required to measure the distribution of particle trajectories across the wafer.

Kinematics Parameters and Sliding Length

Clarkson University

Sliding distance of each particle inside each area element is calculated during polishing time.



Sliding Distance, MRR and WIWNU

Material volume removed based on particle trajectory length:

$$\Delta V(x,y) = k_p\, p(x,y) L(x,y)$$

⇩

$$MRR_v = \frac{\Delta V(x,y)}{T_p} = k_p(R)\, p(x,y) \frac{L(x,y)}{T_p}$$

Uniform pressure profile

Mono-dispersed particles

⇨

$$MRR_v = \underbrace{\frac{k_p(R)\, p}{T_p}}_{const} \times L(x,y)$$

Hence Sliding distance distribution is an indicator of **WIWNU**

⇩

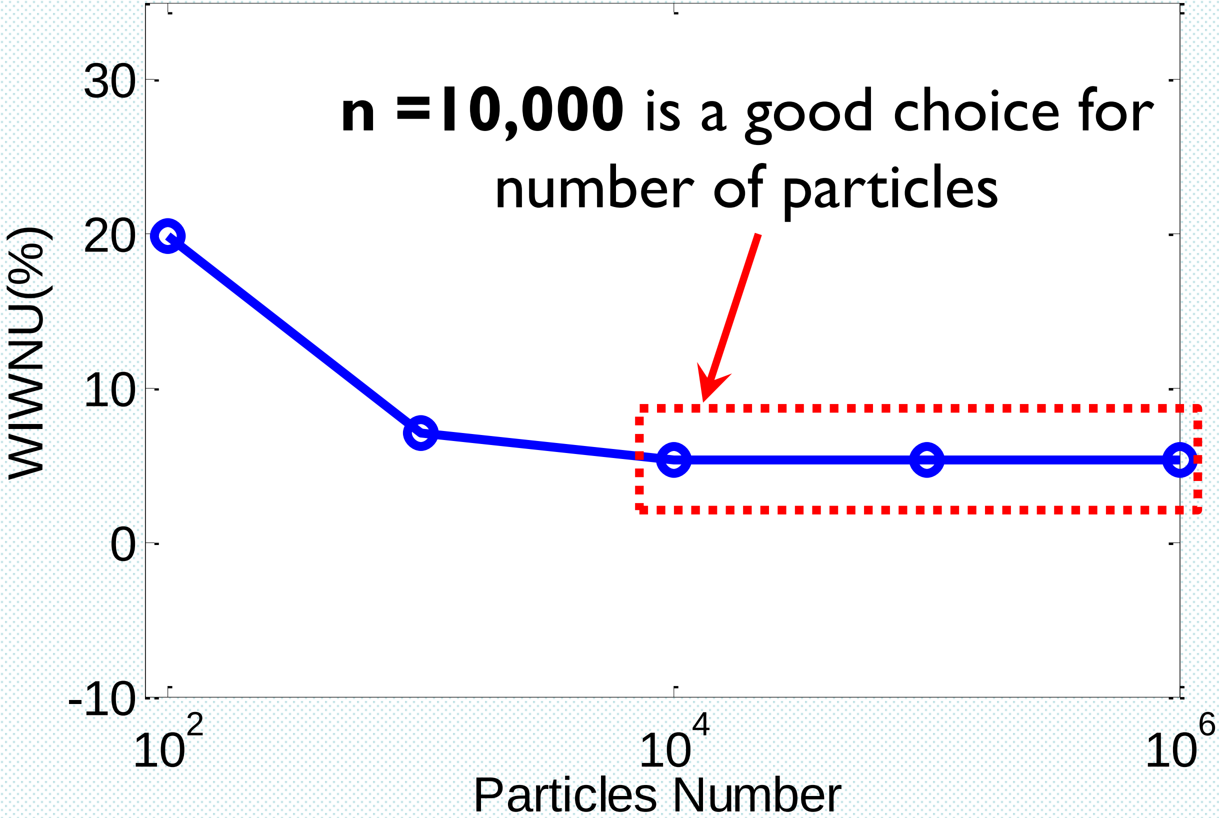
$$WIWNU(\%) = \frac{\sigma_{MRR}}{MRR_{mean}} \times 100 = \frac{\sigma_L}{L_{mean}} \times 100$$

WIWNU vs Active Particle Number

Using large number of particles in simulations is impractical

⇩

So determine the number of active particles that leads to a realistic simulation

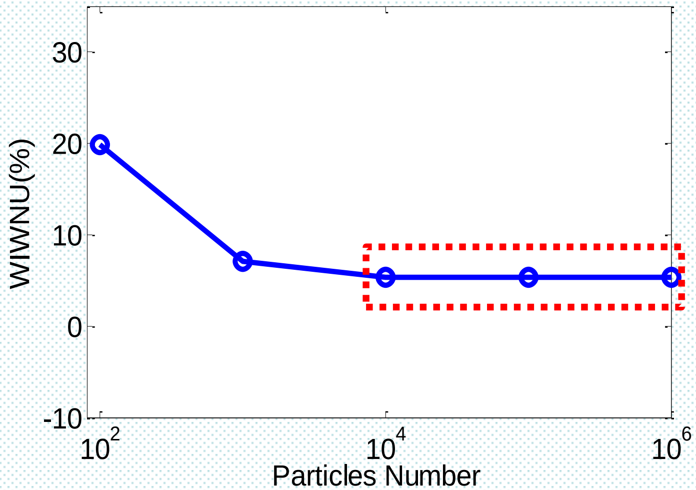


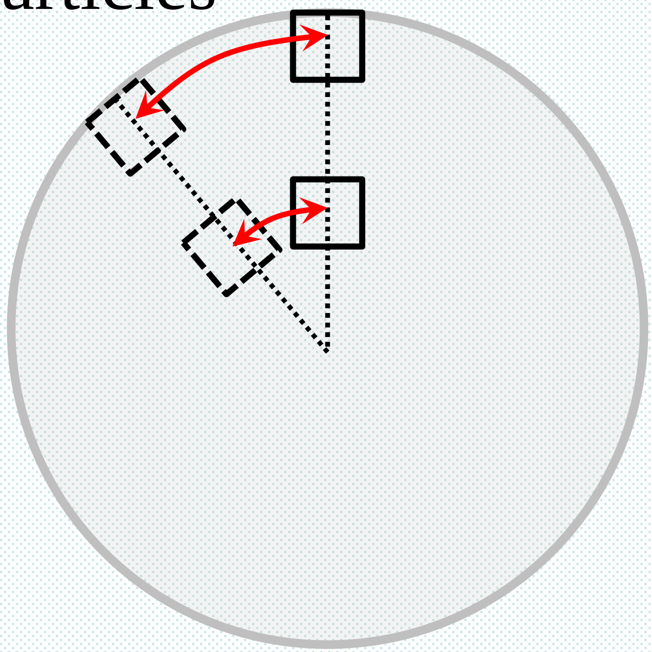
Zhao, Dewen, et al. "Kinematic optimization for chemical mechanical polishing based on statistical analysis of particle trajectories." *Semiconductor Manufacturing, IEEE Transactions on* 26.4 (2013): 556-563.

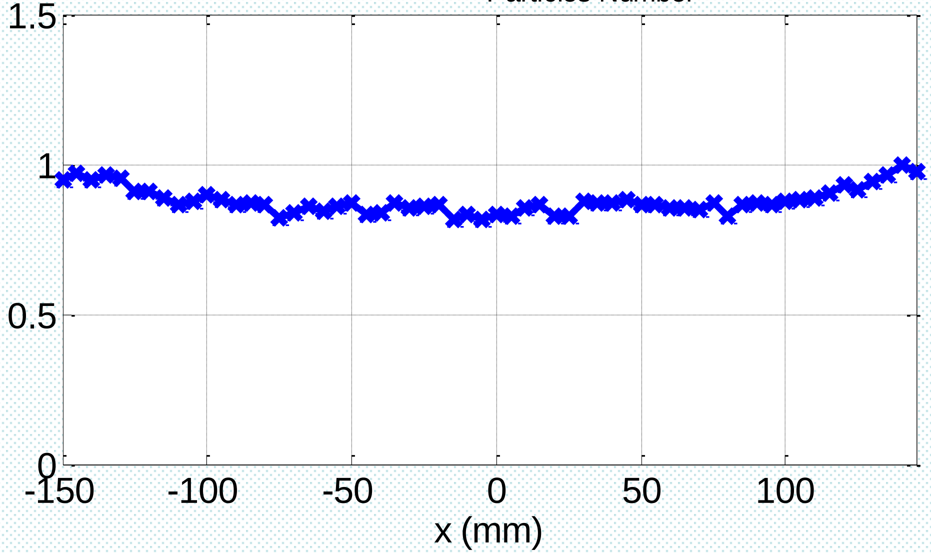
WIWNU Distribution

Question: Whey does WIWNU converge a) to a constant value and b) that is still large?

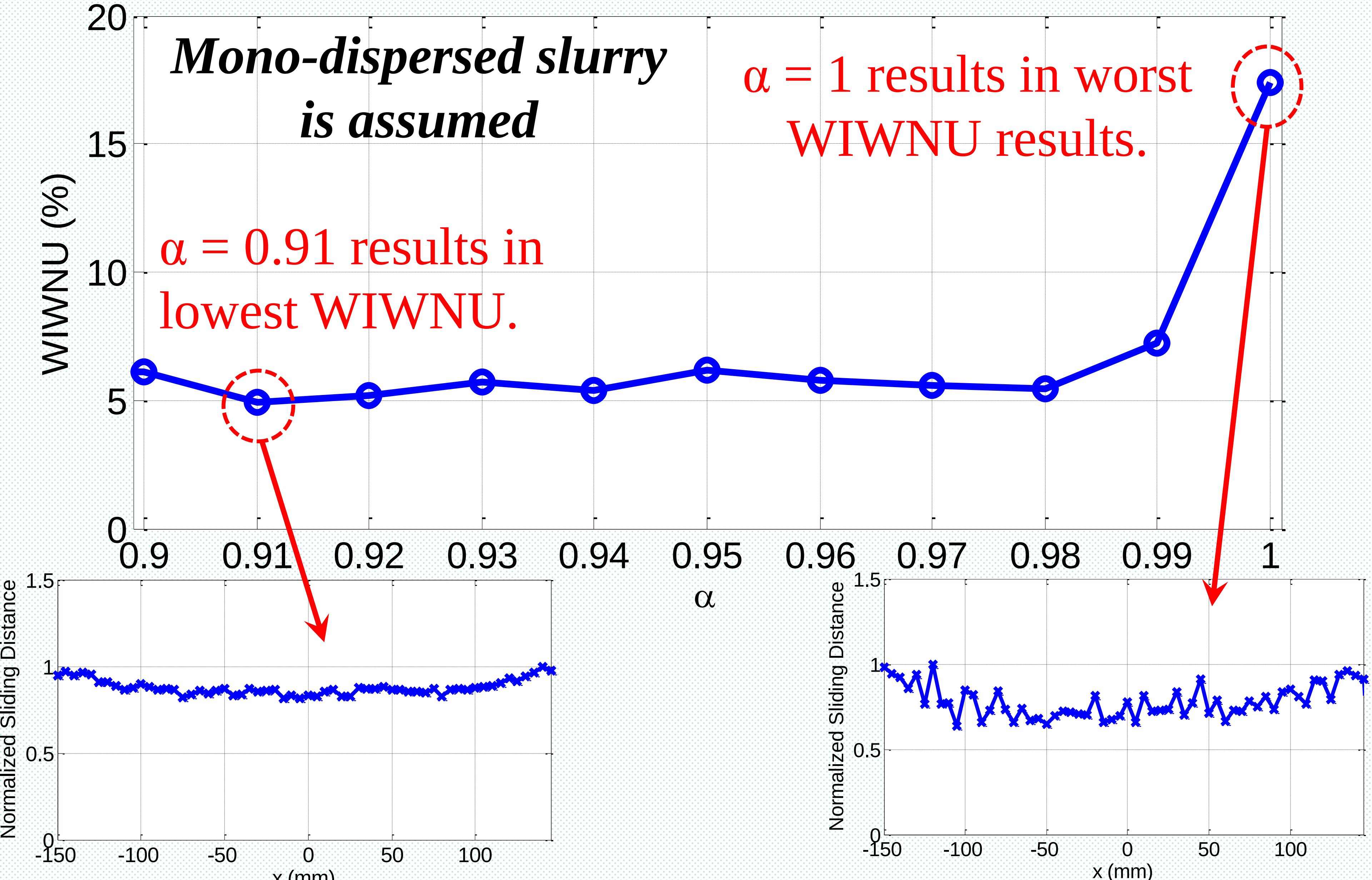
Answer: The MRR increases toward the edge of the wafer even when the whole wafer surface is covered by active particles



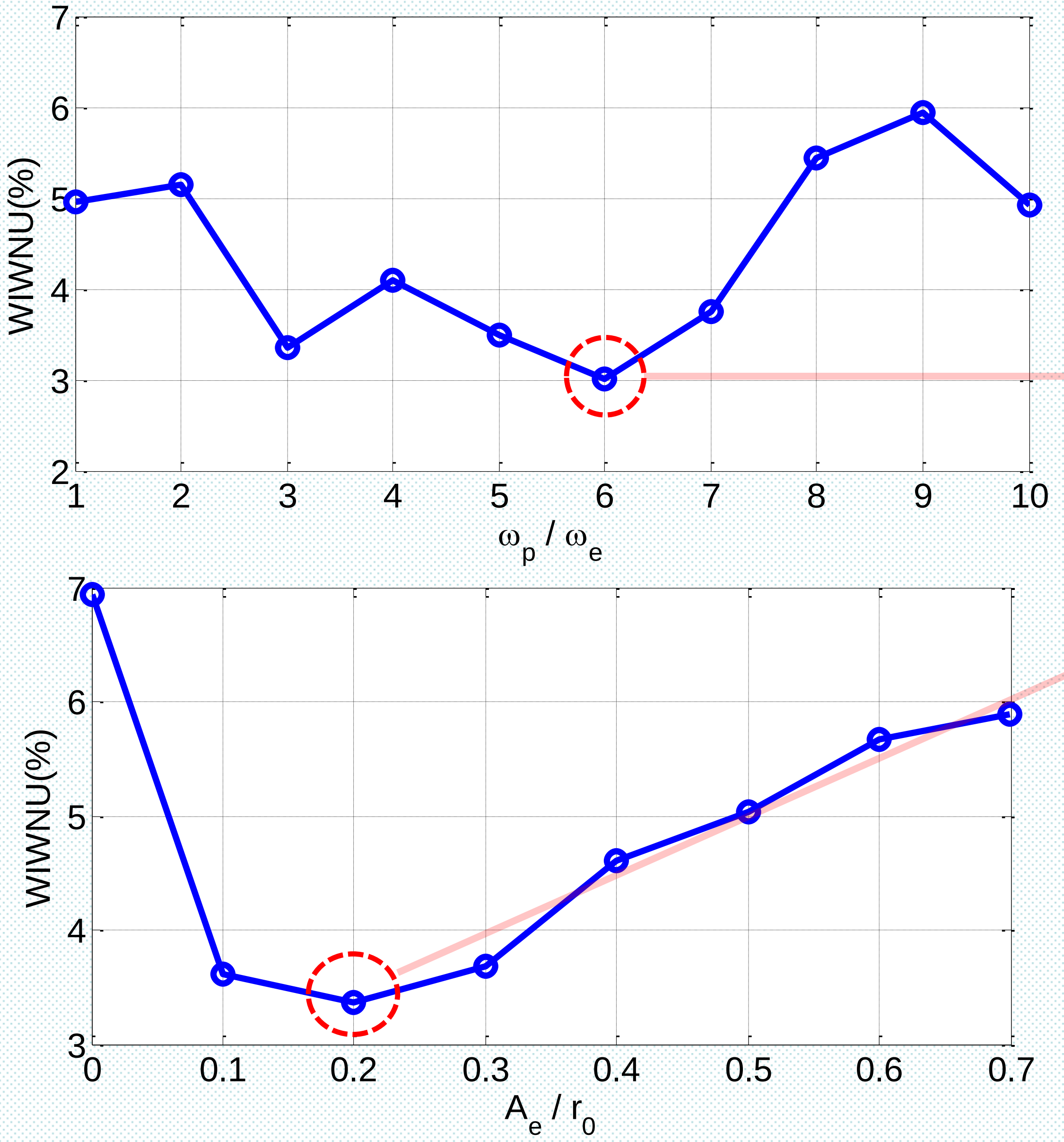




WIWNU vs α Parameter



WIWNU vs Oscillatory Motion



Oscillatory motion

$$e_t = A_e \sin(\omega_e t)$$

$$\omega_e = \frac{\omega_p}{6}$$

$$A_e = \frac{r_0}{5}$$

WIWNU is improved

$$WIWNU(\%) = 3.36\%$$

Quantitative Example of CMP Kinematics

Clarkson University

For polishing of **300 mm** wafers on a rotary-type polishing tool with mono-dispersed slurry:

For $\omega_p = 93 \;\; r/\min$, $e_0 = 200\,mm$ ⇨

$$\begin{cases} \omega_w = \alpha\,\omega_p = 0.91 \times 93 \;\; r/\min \cong 85 \;\; r/\min \\ \omega_e = \dfrac{\omega_p}{6} \cong 15 \;\; r/\min \\ A_e = \dfrac{r_0}{5} = 30\,mm \end{cases}$$

$WIWNU(\%) \cong 4\%$ ***Small variations*** in these numbers create a ***small*** change in the obtained WIWNU

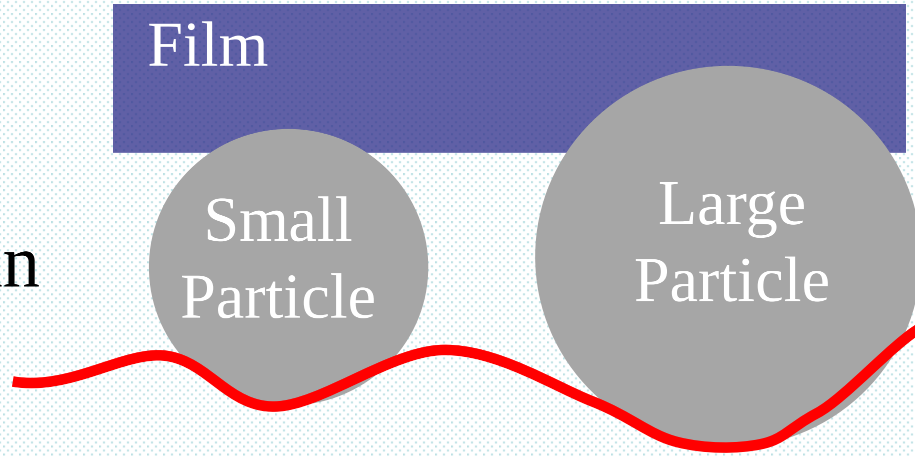
However, some special cases need to be avoided:

$\omega_p = \omega_w = 93 \;\; r/\min$ and $A_e = 0 \;\; or \;\; \omega_e = 0$ $\quad WIWNU(\%) \cong 18\%$

Large Particles Influence on WIWNU

Clarkson University

MRR depends on the size of the abrasives



When film thickness is larger than particle penetration depth

⇩

Particle size dependency of MRR is projected in the Preston's constant

$$k_p(R) \propto R^2$$

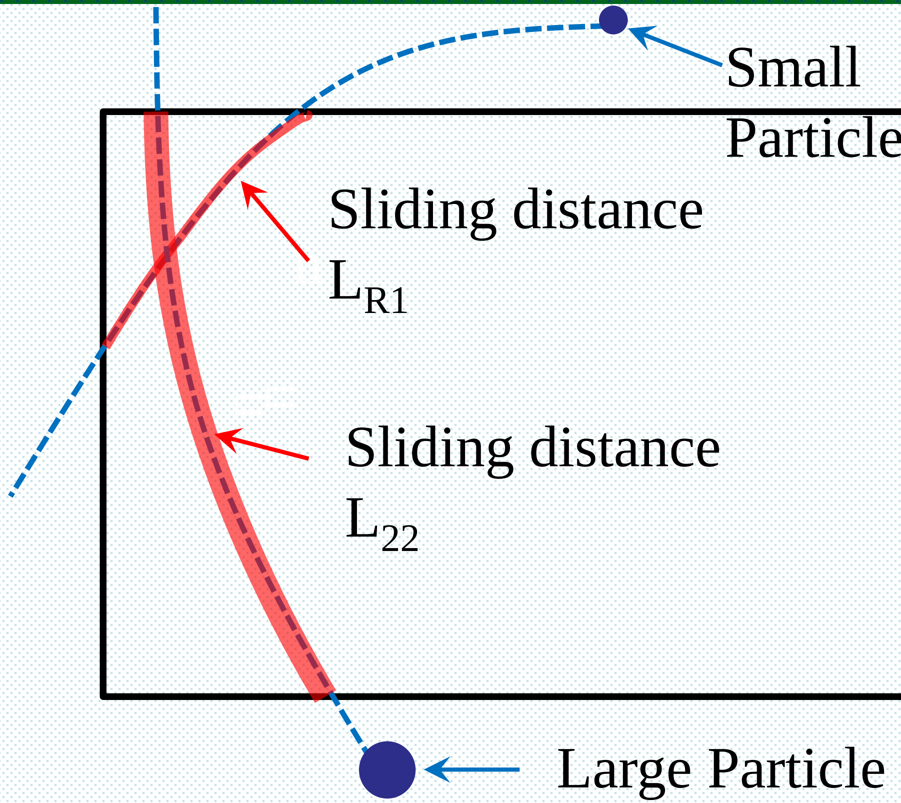
⇩

When large particles are present in the slurry along with the nominal particle size

Large and small particles effects will both be projected in the MRR profile.

Qin, Kuide, Brij Moudgil, and Chang-Won Park. "A chemical mechanical polishing model incorporating both the chemical and mechanical effects." Thin Solid Films 446.2 (2004): 277-286.

Large Particles Influence on WIWNU



$$MRR_v = \frac{k_p p}{T_p} R_1^2 \left[L_{R_1} + (R_2 / R_1)^2 L_{R_2} + (R_3 / R_1)^2 L_{R_3} + \ldots + (R_n / R_1)^2 L_{R_n} \right]$$

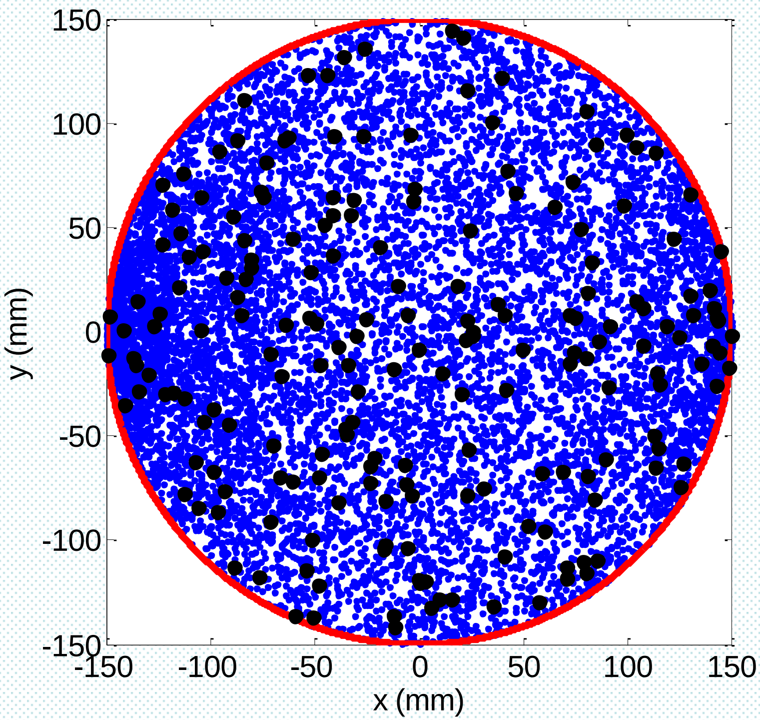
$$WIWNU(\%) = \frac{\sigma_{MRR_v}}{MRR_{T\,mean}} \times 100$$

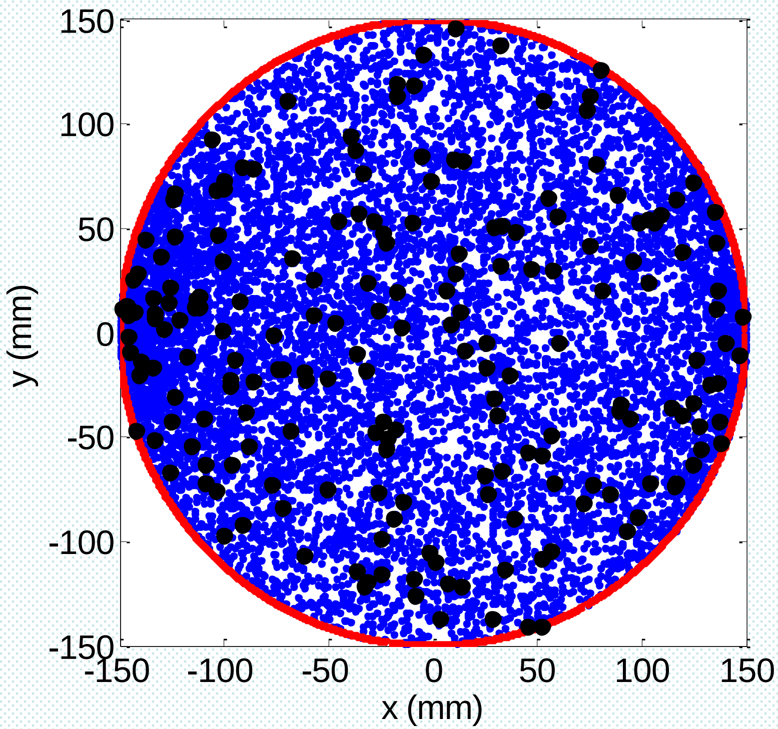
Effect of Large Particles

The number of larger particles is assumed to be **1%-5%** of the total number of active particles

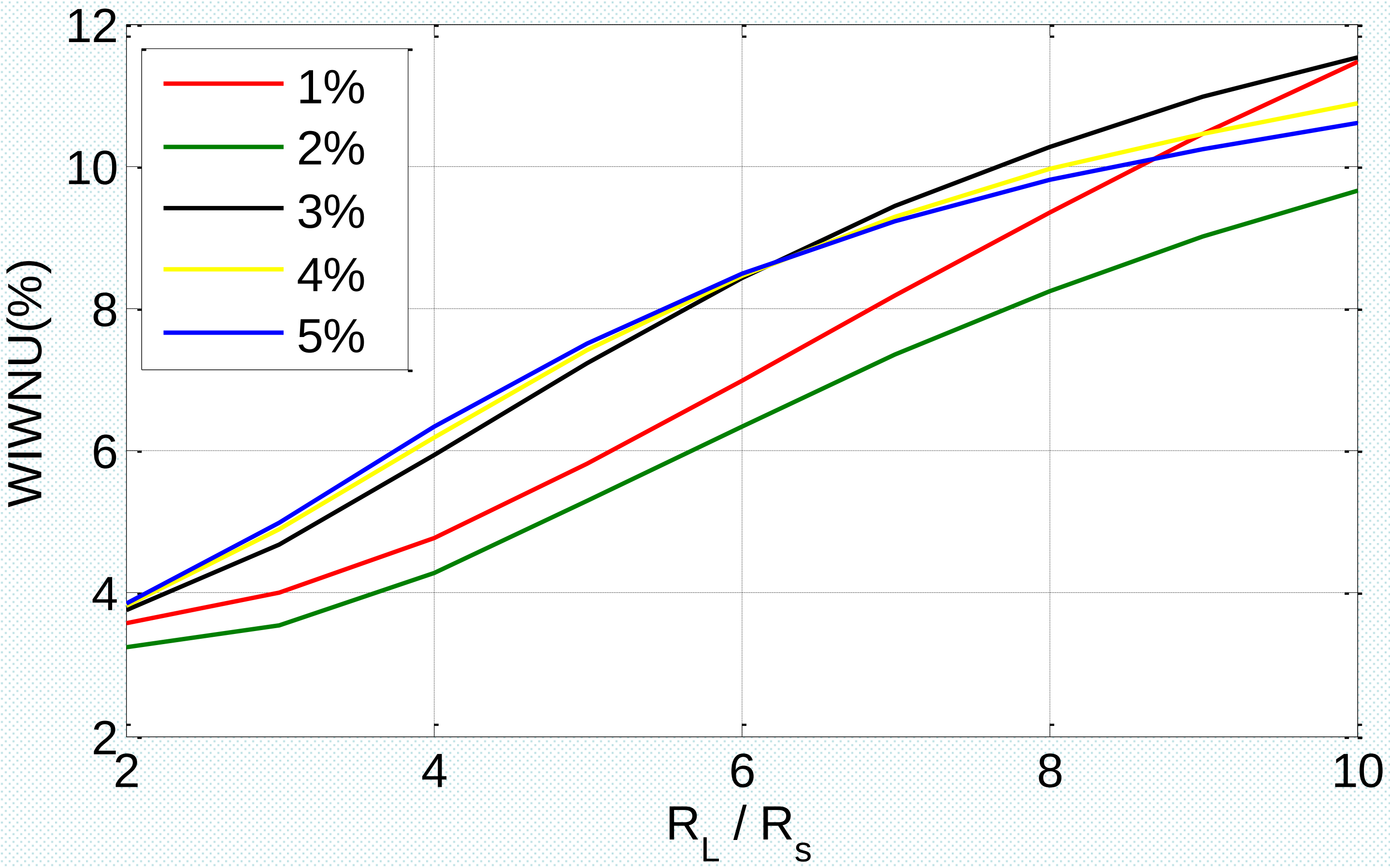
⇩

Trajectories of large particles are calculated while changing their position every **2 seconds**





Large Particles Size and Concentration Effects



Large particles ***size*** can drastically deteriorate WIWNU indicating the significance of a proper slurry filtration process.

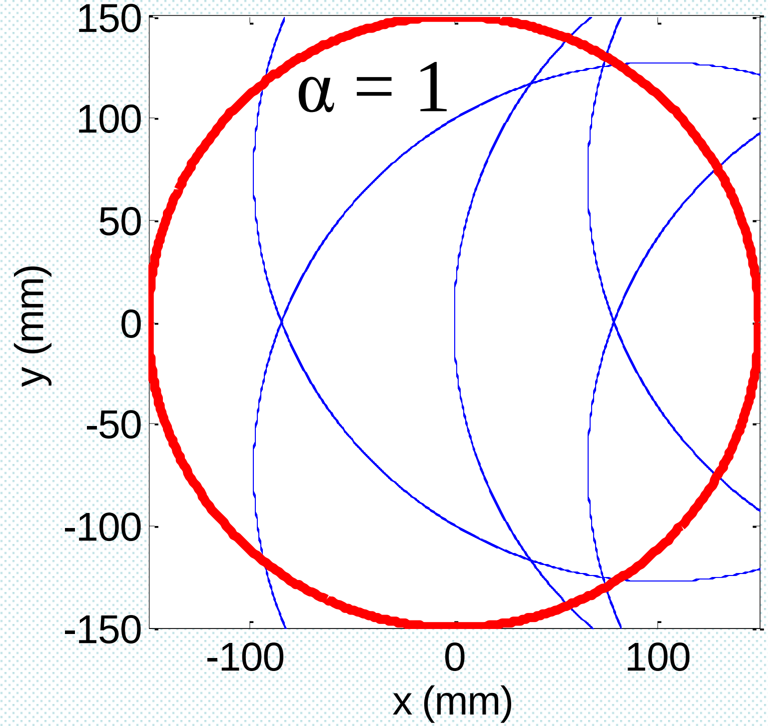
Scratch Growth

Clarkson University

For the special case of α = 1 ($\omega_p = \omega_w$), since each particle travels the same path over and over during the polishing

Large particles and undesired debris can create major scratches on the wafer surface.

Scratch growth on a constant path



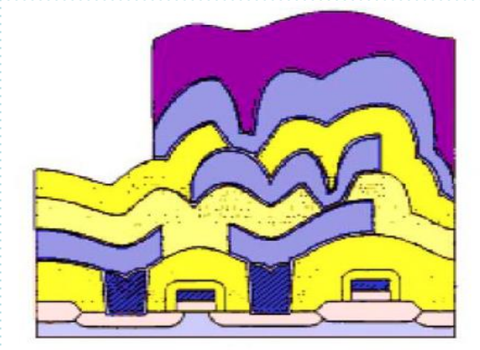
For α ≠ 1 ($\omega_p \neq \omega_w$), since each particle travels various paths during the polishing the effect of large particles is distributed across the wafer which may minimize their unwanted effects

Conclusions and Remarks

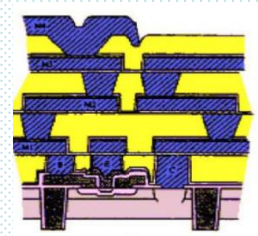
Clarkson University

- A mathematical model to describe particle trajectories during polishing was developed.
- MRR and WIWNU were determined based on the extracted particle trajectories.
- The results showed that $\omega_w=\omega_p$ leads to the worst MRR uniformity.
- When $\omega_w= 0.91\ \omega_p$, the most uniform MRR is obtained.
- The oscillatory motion frequency and amplitude can also be optimized to improve MRR profile uniformity.
- This model is capable of explaining the effect of large particles on WIWNU and scratch growth.

Questions and Comments



Life Before CMP



Life After CMP

Thank you for your attention.