Dynamics of the septum during cell division

Dual Degree Project Stage-II

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Department of Physics
Indian Institute of Technology Bombay

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Outline

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What is septum?
Septum Dynamics

- Visco elastic material
- Activity due to myosin molecular motors
- Diameter of the septum $\sim 10\mu$m. Dynamics at micro scale.

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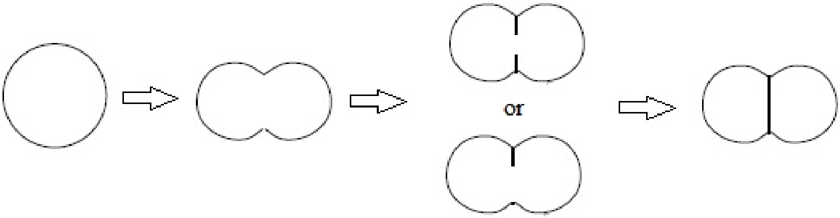

Symmetric and Asymmetric Closure
Septum Dynamics

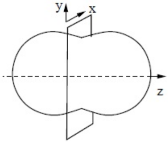

Figure: Septum Plane during cell division

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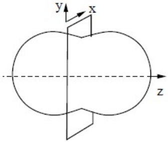

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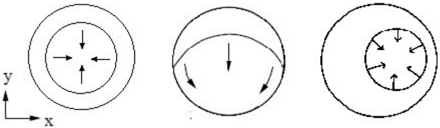

Figure: Cross-section of septum plane: Symmetric and Asymmetric Septum closure

Asymmetric Closure experimentally

Septum Dynamics

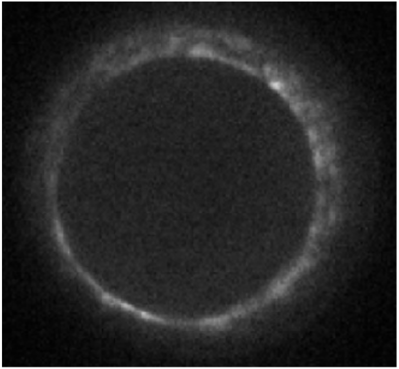

Figure: Experimental movie (obtained from Stephan Grill's lab, CBG Dresden) showing asymmetric septum closure

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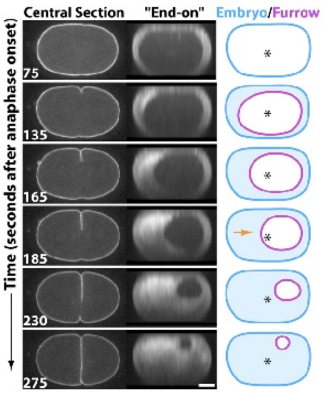

Figure: Time evolution of Septum closure

Outline

Image extraction methods

Image analysis

- To analyze the video, extract a time series of snapshots and analyze them.
- Method 1
  - Using mmreader and avireader in Matlab
  - Difference in number of rows, columns and colour channels
  - Inconsequential. Abandoned.
- Method 2
  - Using snapshot tool in vlc media player
  - Advantages: Septum visibility
  - Disadvantages: Manual, Inaccurate

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PIV basics; Image analysis

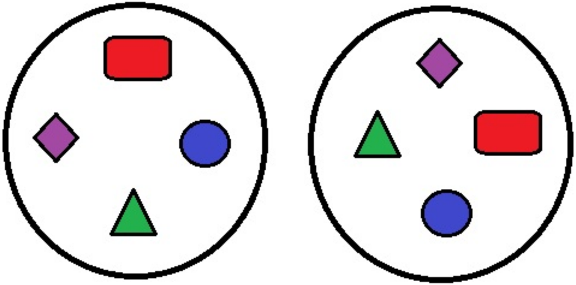

Figure: Two images as input

Particle Image Velocimetry analysis

PIV basics; Image analysis

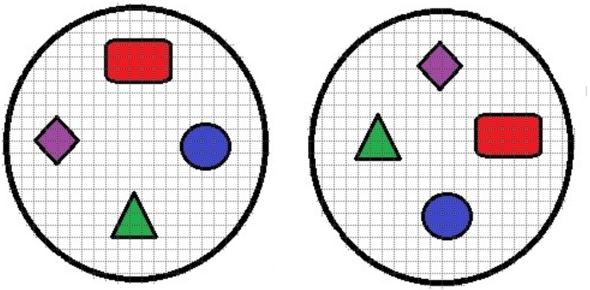

Figure: PIV interrogation regions

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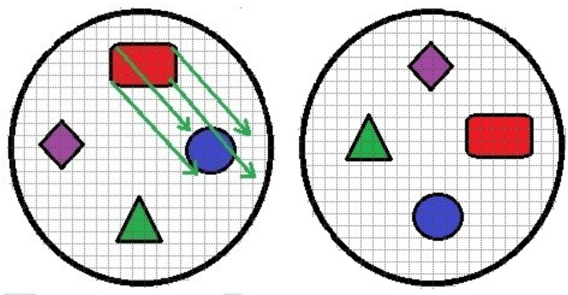

Figure: Mapping using arrows

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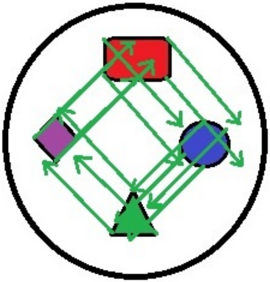

Figure: PIV Output

Parameters on PIV GUI

PIV basics; Image analysis

- Scaling the vectors
- Outlier Filter
- Jump Value
- ROI tool

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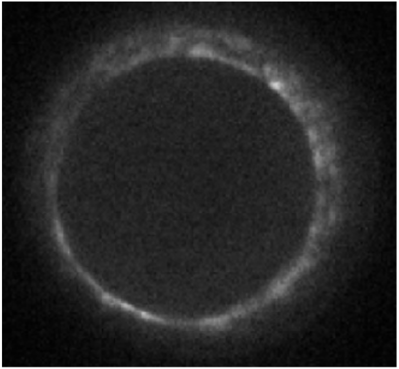

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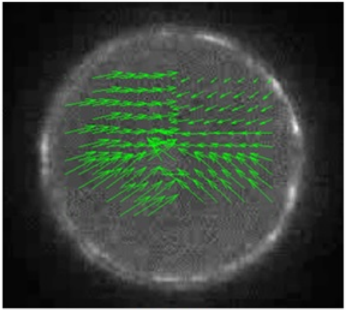
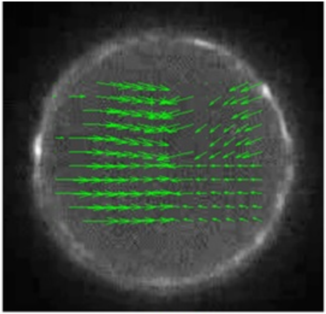


(a) 10-20



(b) 20-30

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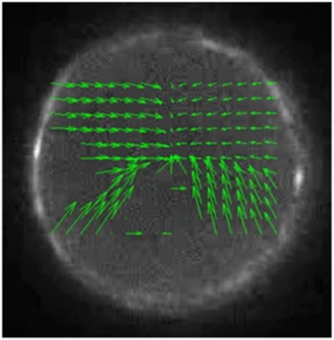
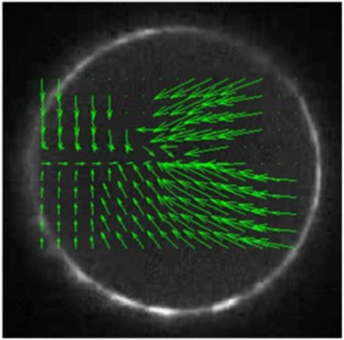


(c) 30-40



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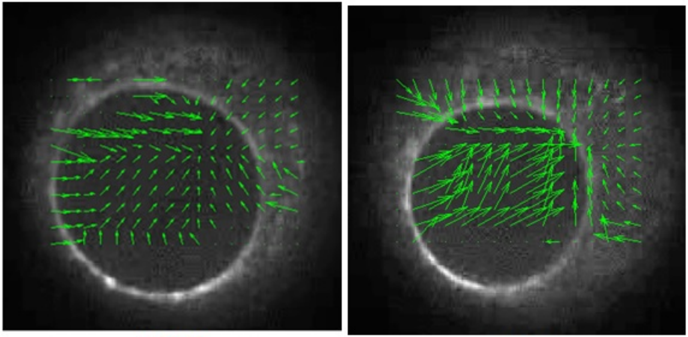

(g) 70-80 (h) 80-85

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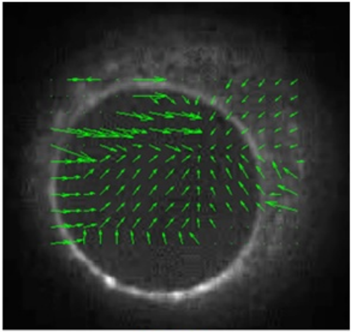

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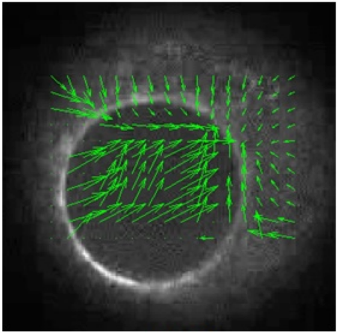

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Inference from PIV maps

PIV on snapshots of asymmetric septum closure

- Rotation of the acto-myosin ring is evident as its radius decreases.
- v_ϕ must depend on r.

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Septum dynamics

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$$\rho\left[\frac{\partial v}{\partial t} + (v.\nabla)v\right] = -\nabla p + \eta\Delta v + \left(\zeta + \frac{1}{3}\eta\right)\nabla(\nabla.v)$$

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$$\nabla.v = 0 \text{ which becomes}$$

$$\frac{1}{r}\frac{\partial(rv_r)}{\partial r}\frac{1}{r}\frac{\partial(v_\phi)}{\partial \phi} + \frac{\partial v_z}{\partial z} = 0$$

Defining the system
Basic equations; Septum dynamics

In cylinderical co-ordinates:

Defining the system

Basic equations; Septum dynamics

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Defining the system

Basic equations; Septum dynamics

Stress-velocity relations in cylindrical co-ordinates:

- $\sigma_{rr} = -p + 2\eta \frac{\partial v_r}{\partial r}$
- $\sigma_{r\phi} = \eta(\frac{1}{r}\frac{\partial v_r}{\partial \phi} + \frac{\partial v_\phi}{\partial r} - \frac{v_\phi}{r})$
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Septum dynamics

At outer periphery the velocity boundary conditions are:

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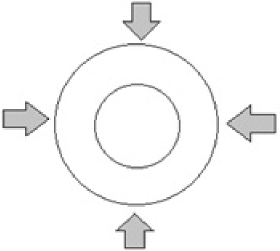

Figure: ϕ symmetric vesicle addition through the outer rim

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Different approaches that didn't work

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- Case 1: $v_r = v_r(r), v_\phi = 0$
- Case 2: $v_r = v_r(r, \phi), v_\phi = 0$
- Case 3: $v_r = v_r(r), v_\phi = v_\phi(r)$
- Case 4: $v_r = v_r(r, \phi), v_\phi = v_\phi(r, \phi)$: Not possible to deal with analytically

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Streamfunction formalism

Different approaches that didn't work; Septum dynamics

- Streamfunction ϕ^S obeys $v = \nabla\phi^S \times \hat{z}$
- In terms of ϕ^S
  $v = v_r\hat{r} + v_\phi\hat{\phi} = \frac{1}{r}\frac{\partial\phi^S}{\partial\phi}\hat{r} - \frac{\partial\phi^S}{\partial r}\hat{\phi}$
- Advantages:
  - Equation of continuity automatically satisfied
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- Doesn't work due to the conflict b/w
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- Advantages:
  - Equation of continuity automatically satisfied
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Different approaches that didn't work; Septum dynamics

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Working theoretical model

Lubrication approximation; Septum dynamics

- Proceed with Case 3 above i.e. assume $v_r = v_r(r), v_\phi = v_\phi(r)$
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Lubrication approximation; Septum dynamics

Under these conditions stress velocity relations reduce as

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- $\frac{\partial \sigma_{rr}}{\partial r} + \frac{1}{r}\frac{\partial \sigma_{r\phi}}{\partial \phi} + \frac{1}{r}(\sigma_{rr} - \sigma_{\phi\phi}) = 0$
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Working theoretical model

Lubrication approximation; Septum dynamics

- Substituting, we get
  - $r^2 \frac{\partial^2 v_r}{\partial r^2} + r \frac{\partial v_r}{\partial r} - v_r$
  - $r^2 \frac{\partial^2 v_\phi}{\partial r^2} + r \frac{\partial v_\phi}{\partial r} - v_\phi$
- Putting $v_r = r^m$ and $v_\phi = r^n$ we get $m, n = \pm 1$. Thus v_r and v_ϕ take the same form
  - $v_r = Ar + \frac{B}{r}$
  - $v_\phi = Ar + \frac{D}{r}$

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Lubrication approximation; Septum dynamics

- Applying the boundary conditions at outer periphery
  - $v_r(R_1) = -v_0$,
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  - $v_r(r) = Ar - \frac{AR_1^2}{r} - \frac{v_0 R_1}{r}$
  - $v_\phi(r) = Cr - \frac{CR_1^2}{r}$
- Applying the boundary condition at inner periphery $\sigma_{rr}(R_2) = \frac{\Sigma}{R_2}$ in symmetric case, we get $A = [\frac{1}{R_1^2+R_2^2}][\frac{\Sigma R_2}{2\eta} - v_0 R_1]$

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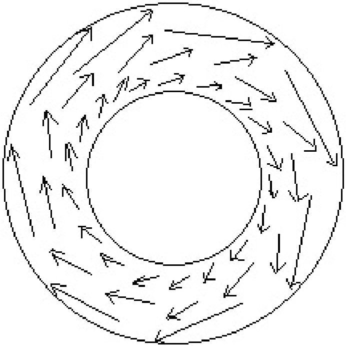

Figure: Schematic representation of the flows under lubrication approximation model showing radial dependence of v_r and v_ϕ

Outline

1. Motivation
   - The Basic Problem of Septum Dynamics
2. Progress towards the solution
   - Image analysis
   - Application of PIV to reveal septum dynamics
   - Theoretical Models
3. Fast Relaxation of the septum post laser ablation
   - Theoretical Approach
   - Image analysis
4. Simulation using phase field formalism
5. Summary and Future scope

Revisiting the system
Septum Dynamics

- 2D viscous tensor components inside septum:

$$\sigma_{rr} = \sigma_0 + 2\eta \frac{\partial v_r}{\partial r},\ \sigma_{\phi\phi} = \sigma_0 + 2\eta \frac{v_r}{r}$$

- Force balance Equation:

$$\partial_r \sigma_{rr} + \frac{1}{r}(\sigma_{rr} - \sigma_{\phi\phi}) = 0$$

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Ablation response

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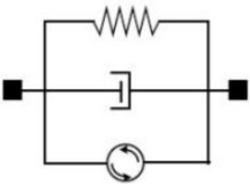

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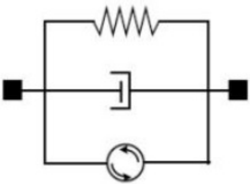

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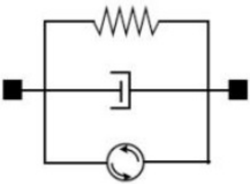

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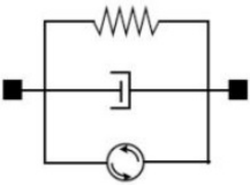

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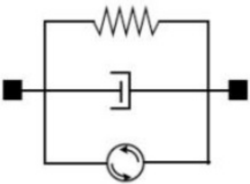

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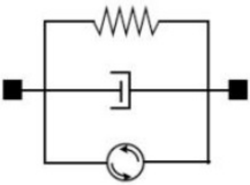

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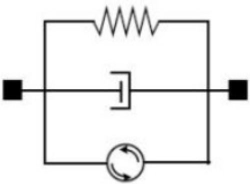

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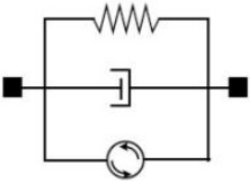

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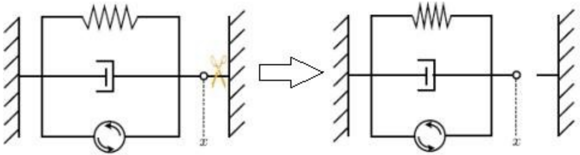

Cortical dynamics post ablation

Ablation response

- Dynamics of the rapid displacements
  $T - kx - \zeta\dot{x} - C = 0$
- The initial condition
  $T(t) = T_0(1 - U(t))$, where $U(t)$ is the unit step function
- Solving this equation,
  $v = \dot{x} = -\frac{T_0}{\eta} e^{-\frac{t}{\tau}}; t > 0$
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Stress balance equation
Theoretical approach

- Radial septum stress $\sigma_r = \sigma_0 + \frac{\eta}{A}\frac{dA}{dt}(1 + \frac{A_0}{A_0 - A})$
- Two components of transverse septum stress at ring boundary:
  - Active component: $\sigma_t^a = \Sigma_0 + \zeta\frac{\dot{u}(r)}{r}$
  - Passive component: $\sigma_t^p = k\frac{u(r)}{r}$
- In 2D, $\sigma_r = \frac{\sigma_t}{r}$ and thus we obtain

$$\sigma_0 + \frac{\eta}{A}\frac{dA}{dt}(1 + \frac{A_0}{A_0 - A}) = \frac{1}{r}(\Sigma_0 + \zeta\frac{\dot{u}(r)}{r} + k\frac{u(r)}{r})$$

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A specific solution
Theoretical approach

- Neglecting the elastic component of the ring,
  $\frac{dA}{dt} = -\frac{\sigma_0 A}{\eta} \frac{A_0 - A}{2A_0 - A}$
- Solving this we get,
  $A(t) = \frac{1}{2}(e^{-\frac{\sigma_0 t}{\eta}})[e^c \pm e^{\frac{c}{2}}\sqrt{e^c - 4A_0 e^{\frac{\sigma_0 t}{\eta}}}]$

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  $A(t) = \frac{1}{2}(e^{-\frac{\sigma_0 t}{\eta}})[e^c \pm e^{\frac{c}{2}}\sqrt{e^c - 4A_0 e^{\frac{\sigma_0 t}{\eta}}}]$

Outline

Images extracted using method 2

Image extraction; Image analysis

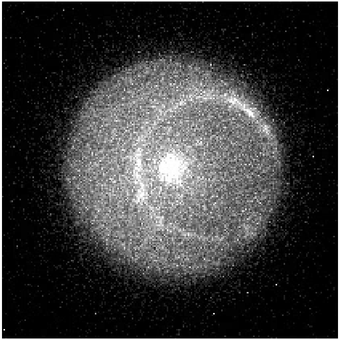

Figure: Movie showing fast relaxation of septum post laser ablation

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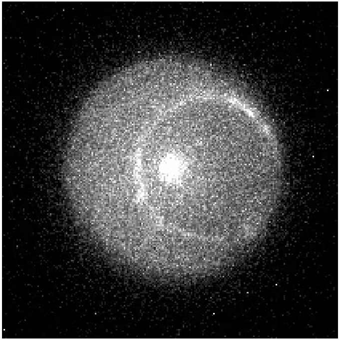

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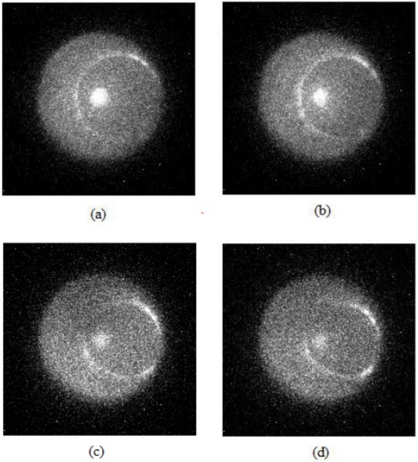

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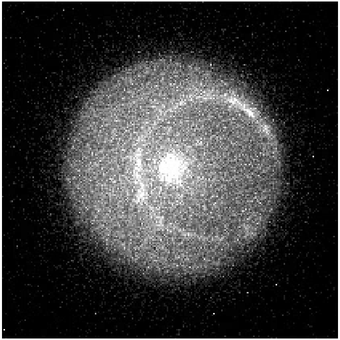

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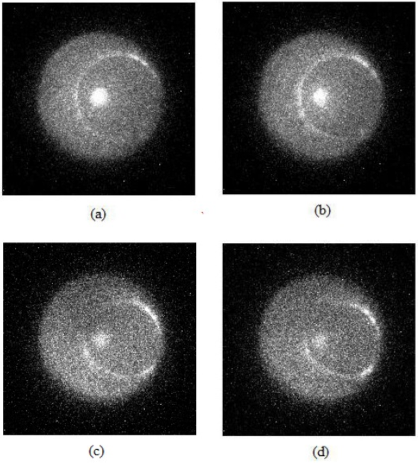
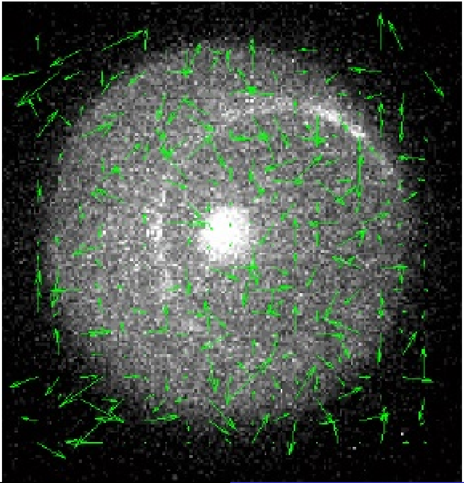


PIV on extracted images; Inconclusive

PIV application; Image analysis



Phase Field formalism
Septum Dynamics

- The dynamic equation for the phase field is
  $\frac{\partial \phi}{\partial t} = -u.\nabla \phi + \Gamma(\epsilon \nabla^2 \phi - \frac{G'}{\epsilon})$
- $G(\phi) = \phi^2(1-\phi)^2$
- The second module describes the actin network as
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- ϕ takes care of the boundary conditions.

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- Velocity maps obtained from PIV gave way towards theoretical model under lubrication approximation
- Better video quality; Improved velocity maps; Can help resolving the rotation of the ring.
- Area of the septum decreases with time under fast relaxation.
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