

***In situ* synchrotron radiography  
investigation of graphite nodule evolution  
during solidification in ductile cast iron**

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UNIVERSITY OF  
**LEICESTER**

# Cast Iron: The First Man-made Composite

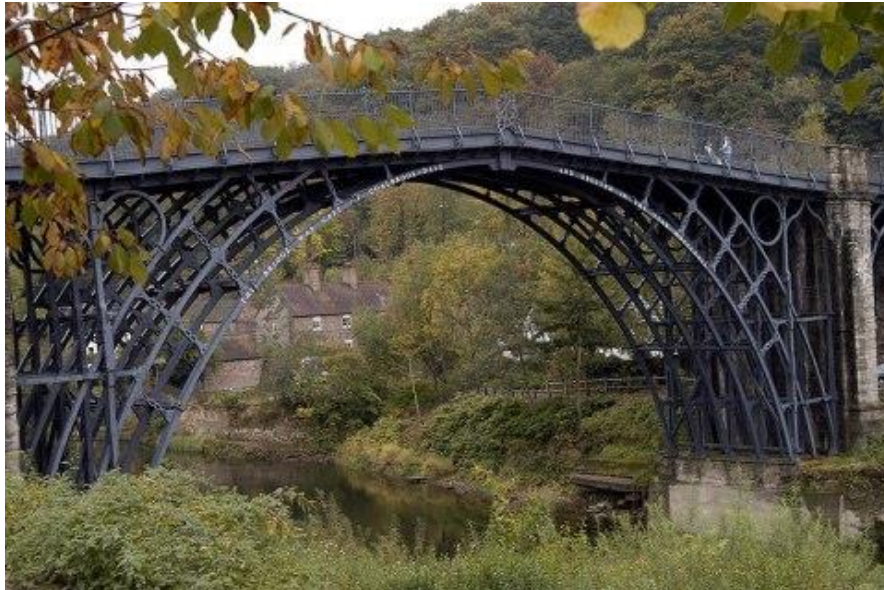


*2500 years of history,  
from ancient origins to  
modern advancements*

*Ding 鼎 from a grave excavated at Yutaishan in Jiangling,  
Hubei, dated to the 4th century BCE [1].*

# Introduction of Cast Iron in Europe

*In the 1400s, iron casting was introduced into Europe...*



*Iron Bridge, Coalbrookdale*



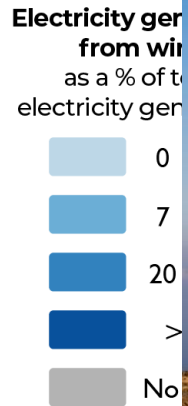
*Royal Pavilion, Brighton*

# Renewable energy

In the 1940s, ductile cast iron was discovered, marking the beginning of a new chapter for cast iron...

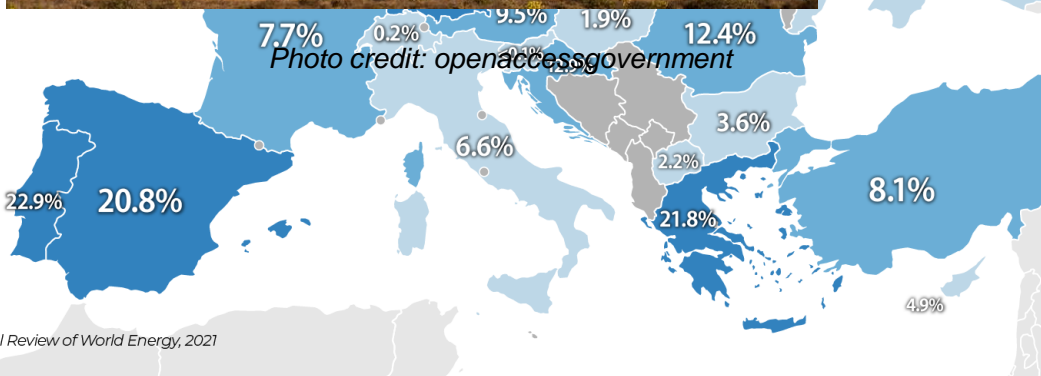
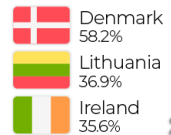
Wind energy generation

Landgeist.com  
@Land\_geist  
@Landgeist



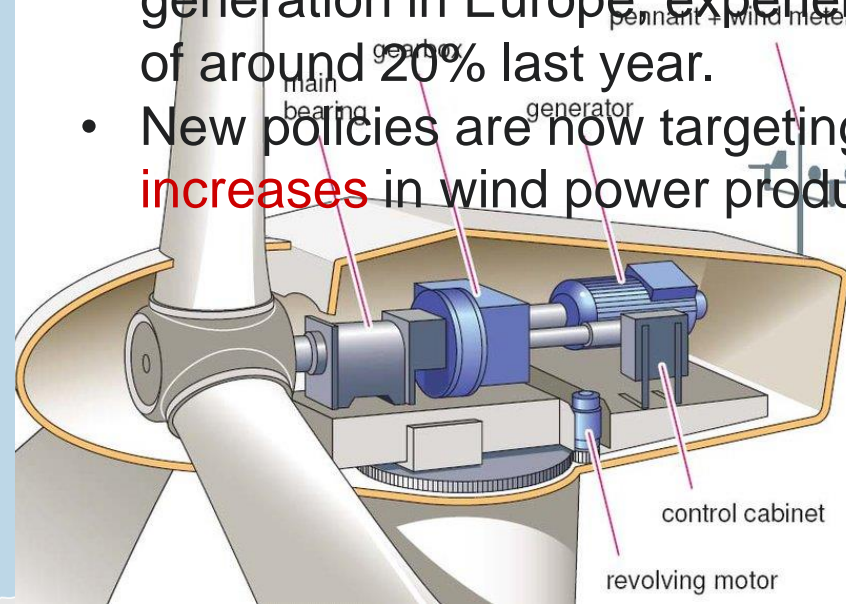
0.1%

Highest



Source: BP Statistical Review of World Energy, 2021

- Wind has **overtaken** coal in electricity generation in Europe, experiencing a growth of around 20% last year.
- New policies are now targeting **further increases** in wind power production in 2024.



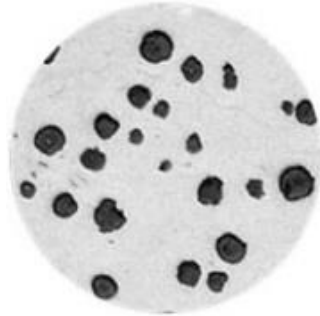
Credit: Seifeddine Benelghali

# Why Choose DCI

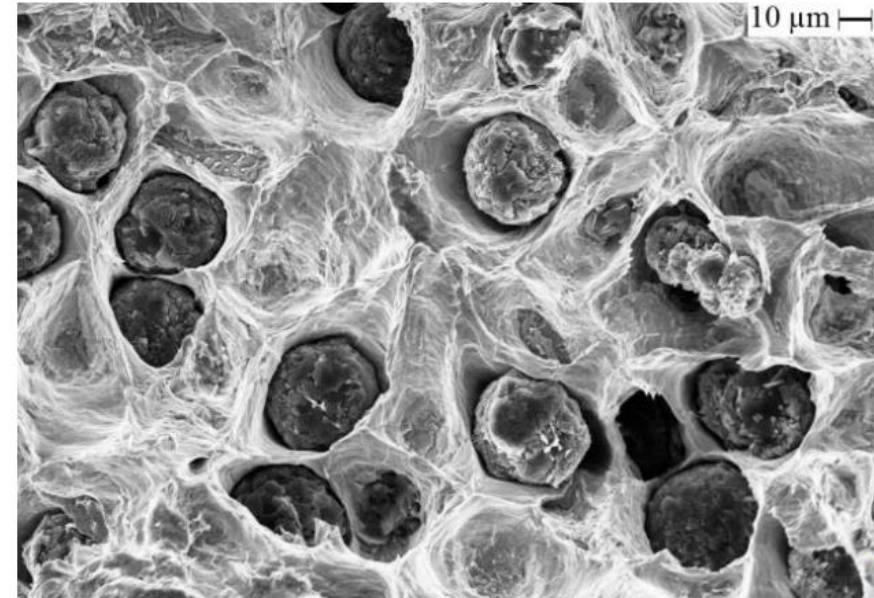
Flaky graphite



Spheroidal graphite



Microstructure



[1]

## Properties

- High Strength-to-Weight ratio
- Excellent Fatigue Resistance
- Damping capacity

# Synchrotron Radiography



*Source: Synchrotron Soleil*

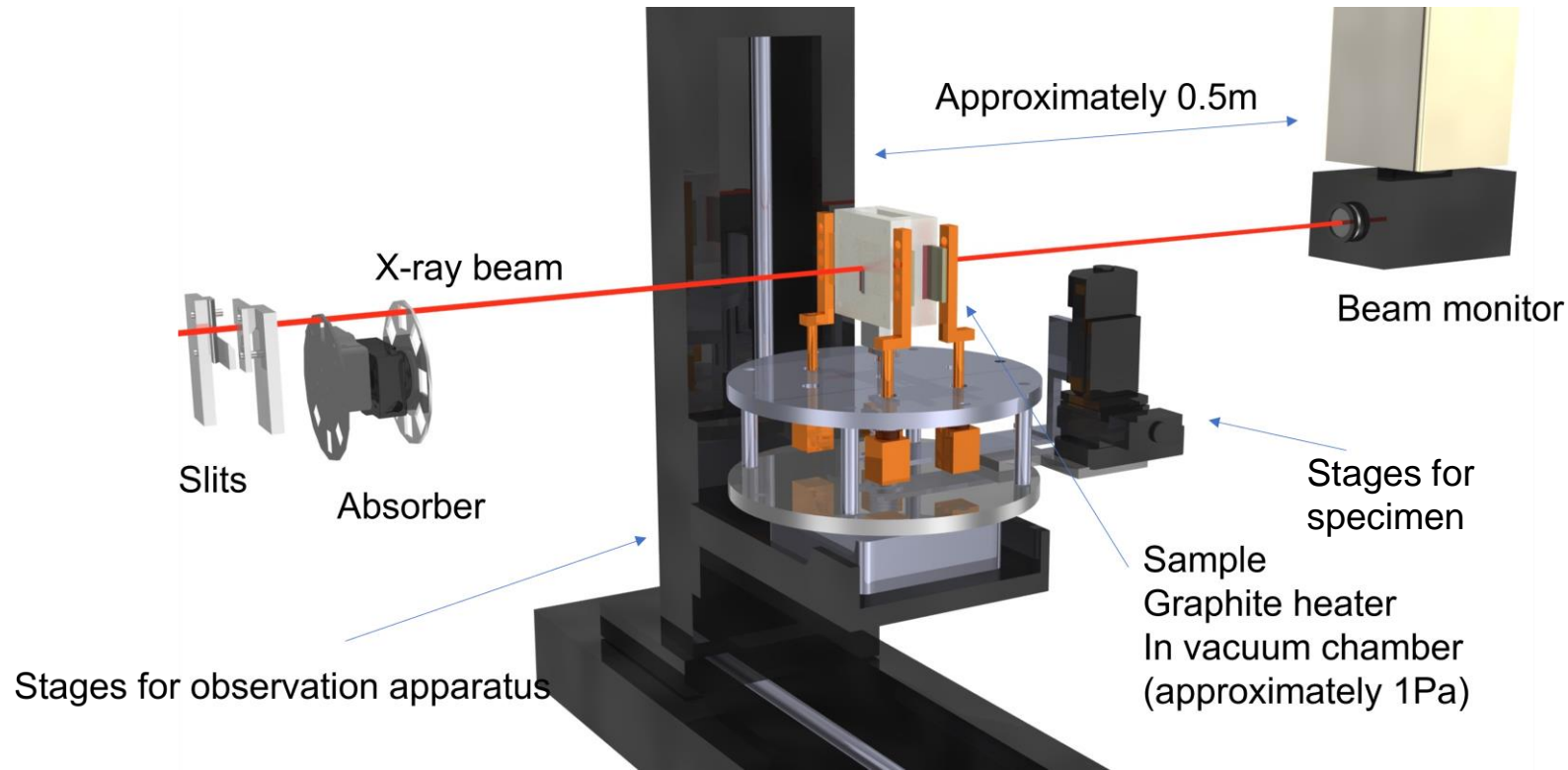
- **High spatial resolution**

Allowing fine details of **small objects** to be obtained

- **High temporal resolution**

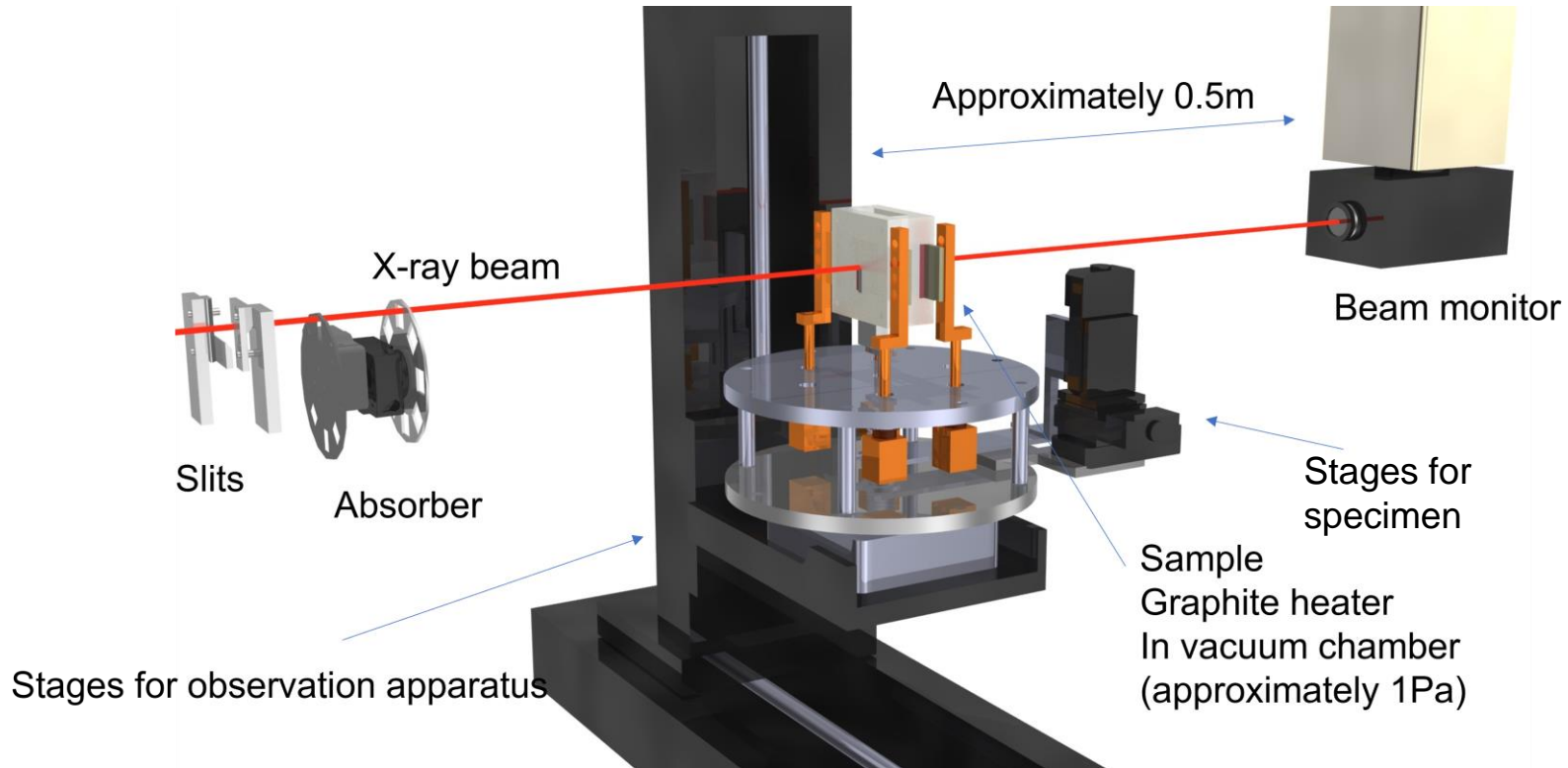
Allowing for **dynamic imaging** of **fast-moving** or **evolving** processes

# Experimental set-up



**Beamline:** BL20XU, SPring-8  
**X-ray energy:** 21keV  
**Pixel size:** 0.5  $\mu\text{m}$  x 0.5  $\mu\text{m}$   
**Frame rate:** 10 fps  
**Specimen dimensions:**  
100mm x 100mm x 100  $\mu\text{m}$   
**Cooling rate:** 30K/min

# Methodology



## Advantages

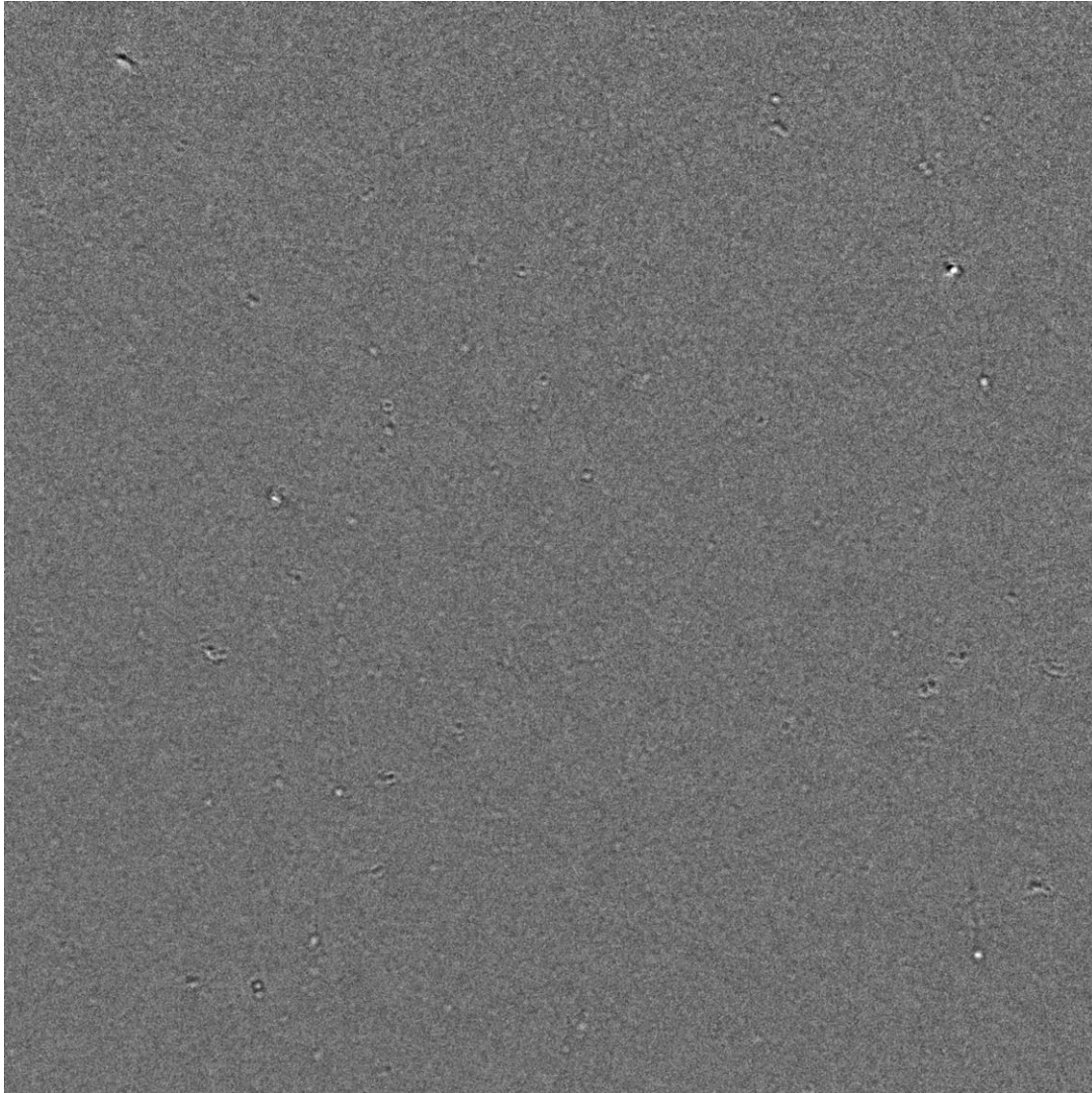
- Fast imaging
- High spatial resolution
- High contrast

## Disadvantages

- 2d
- Geometric constraints



# Data

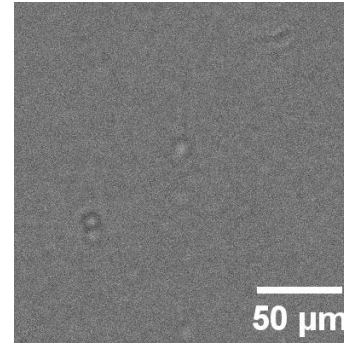


DCI 30K/min 1st

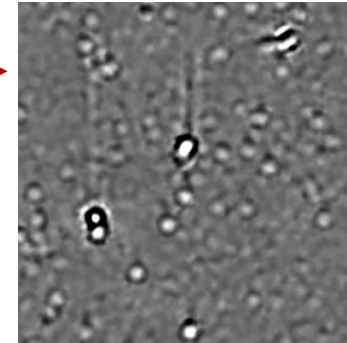
100  $\mu$ m

784.87s

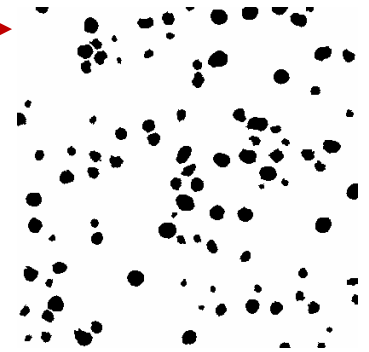
# Image Processing



Original image



Noise2Void+Normalizing



Trainable Weka  
Segmentation

## Data overview

### Content

#### ✓ Inoculant Kinetics

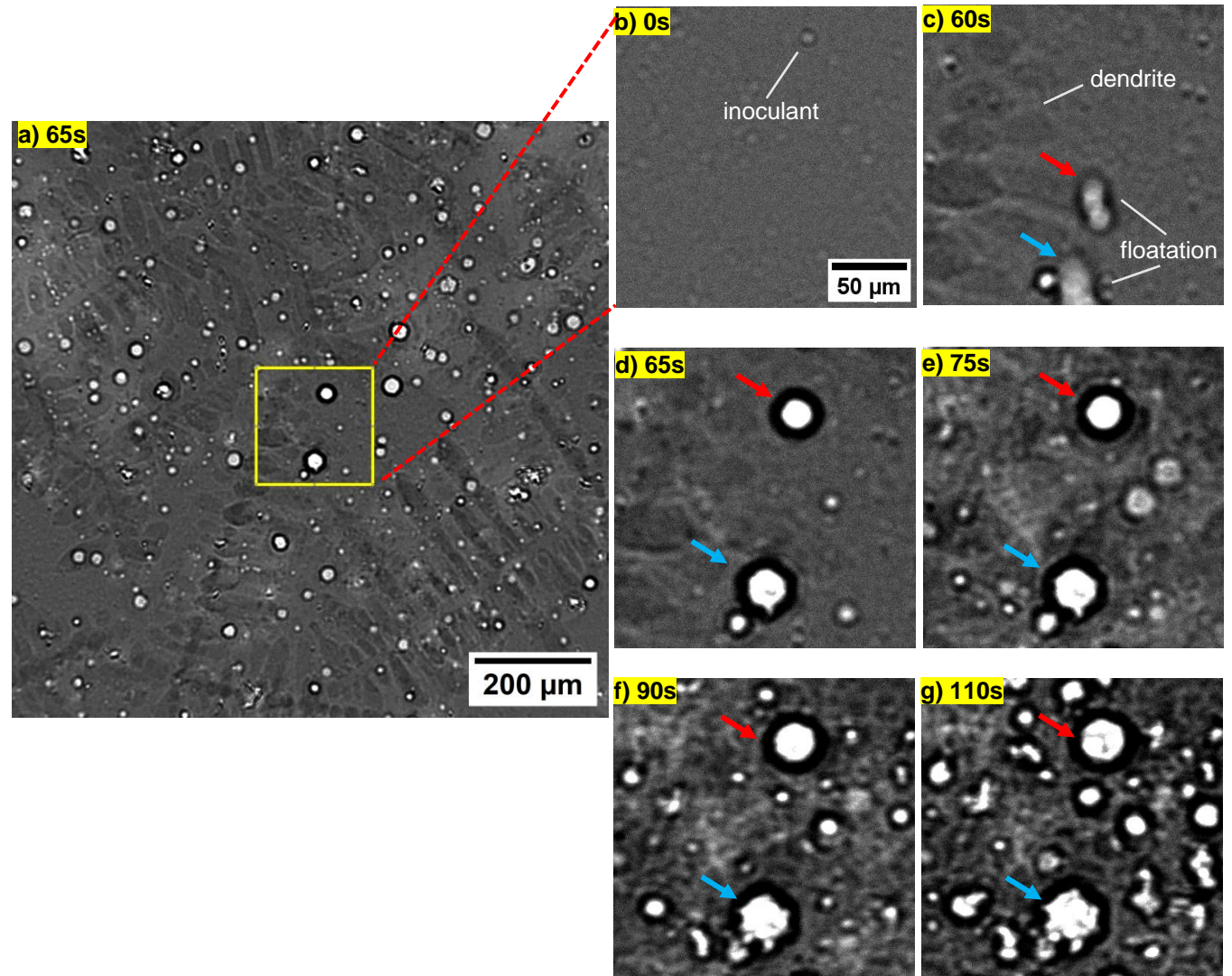
- Distance and Speed

#### Nucleation

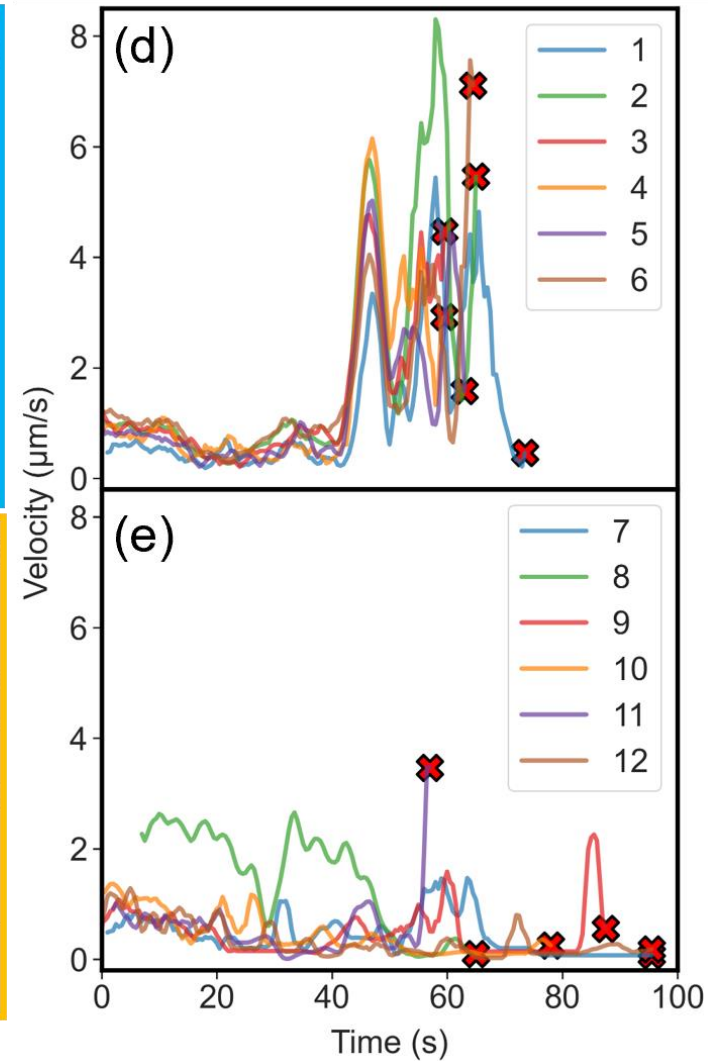
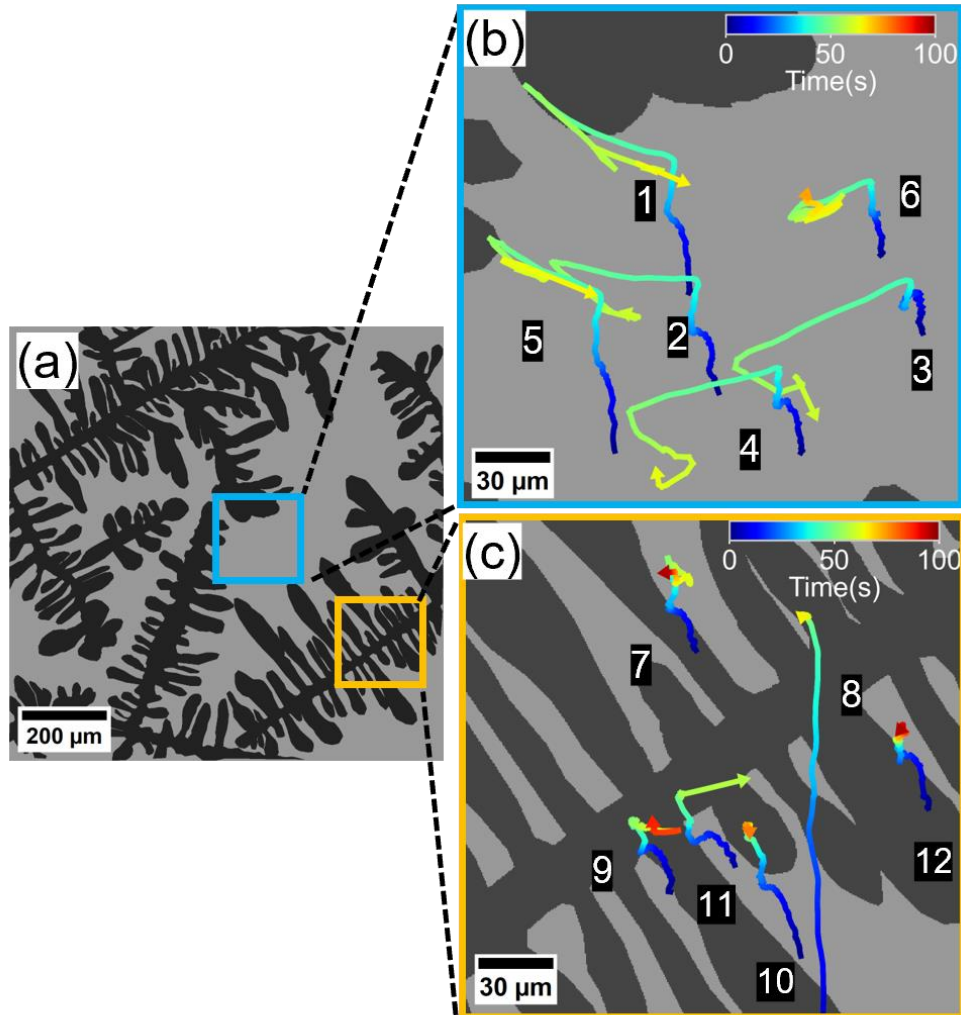
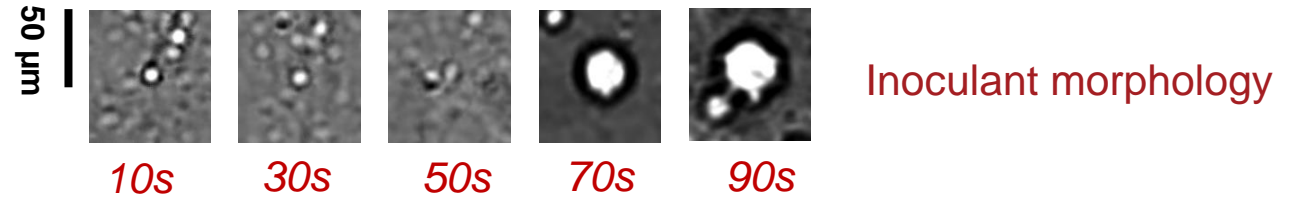
- Three Nucleation Waves
- Spheroidal growth
- Floatation

#### Degenerate Morphologies

- Sphericity change
- Interconnection



# Inoculant Kinetics



## Findings

- Location affects inoculant kinetics.
- Inoculants may not nucleate immediately upon contact with dendrites.
- The morphology of inoculants did not show significant changes before nucleation.

## Content

### Inoculant Kinetics

- Distance and Speed

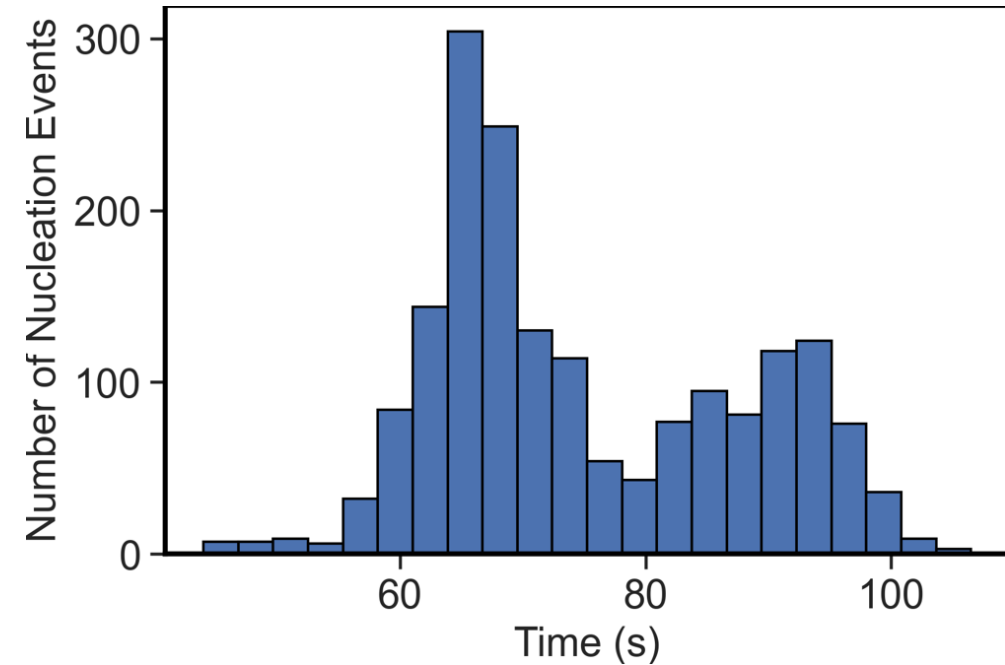
### ✓ Nucleation

- **Three Nucleation Waves**
- **Spheroidal growth**
- **Floatation**

### Degenerate Morphologies

- Sphericity change
- Interconnection

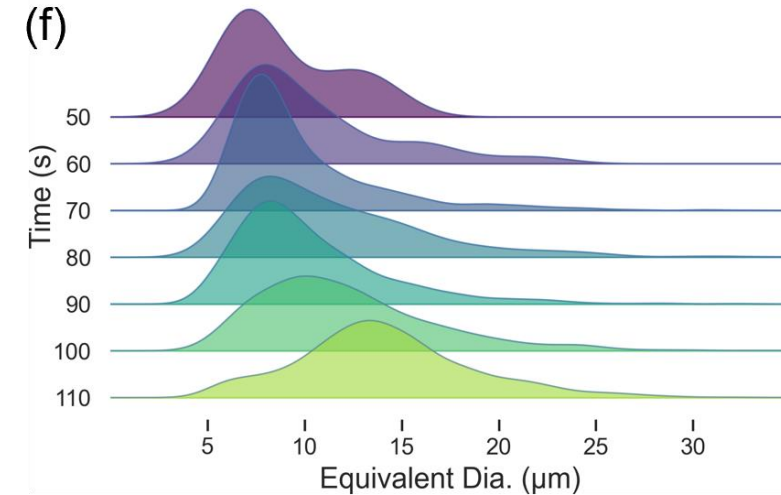
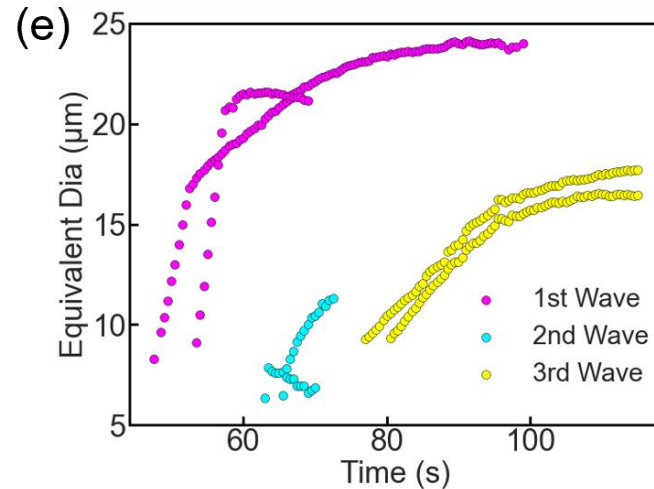
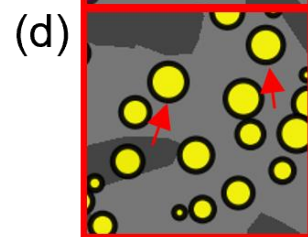
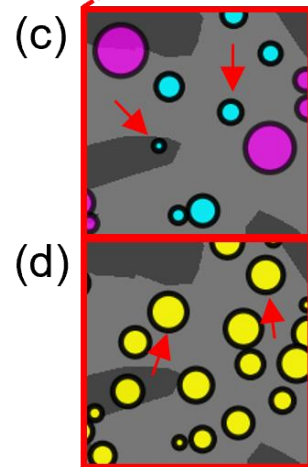
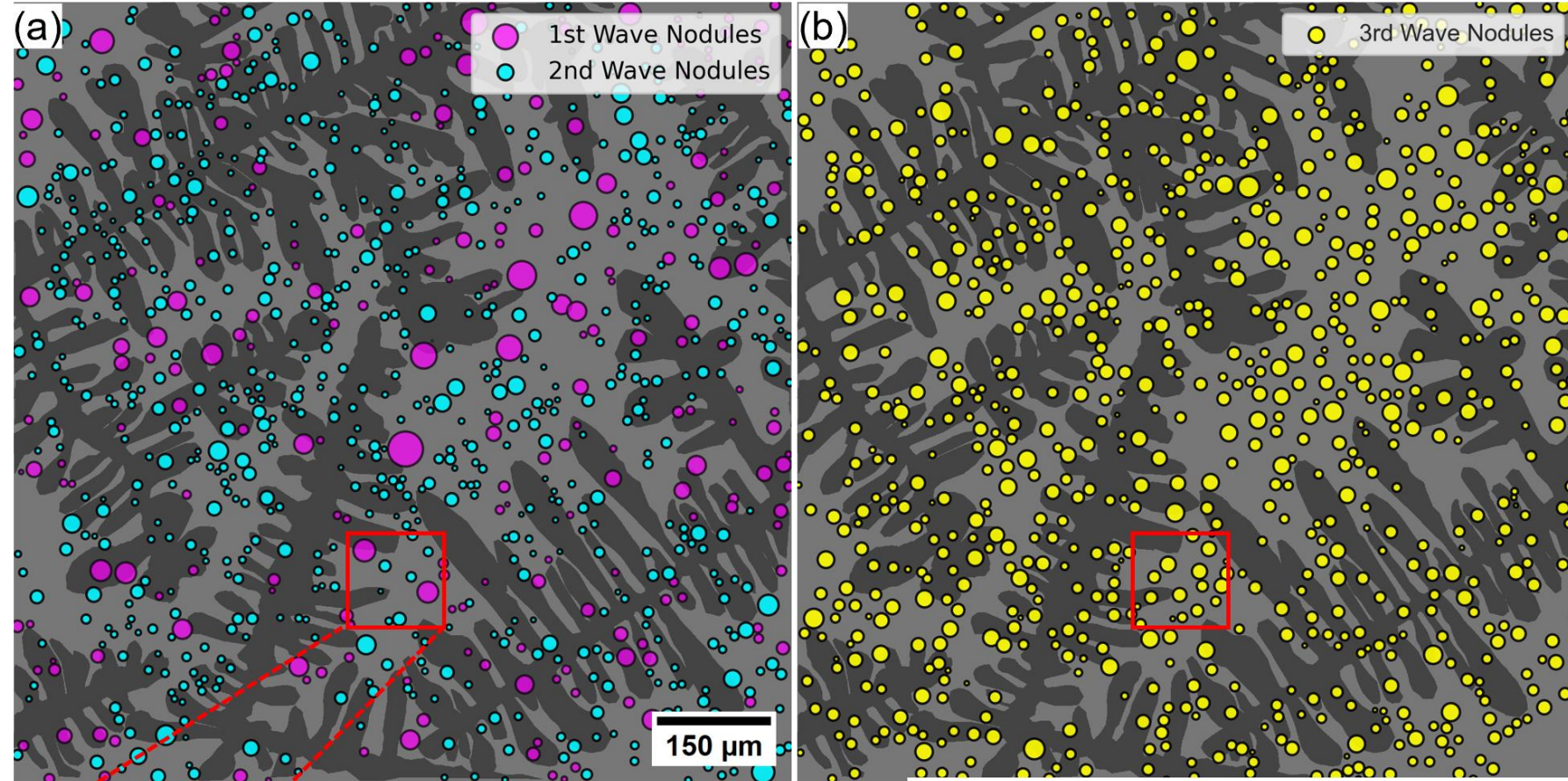
*Distribution of Nucleation Events Over Time*



# Nucleation

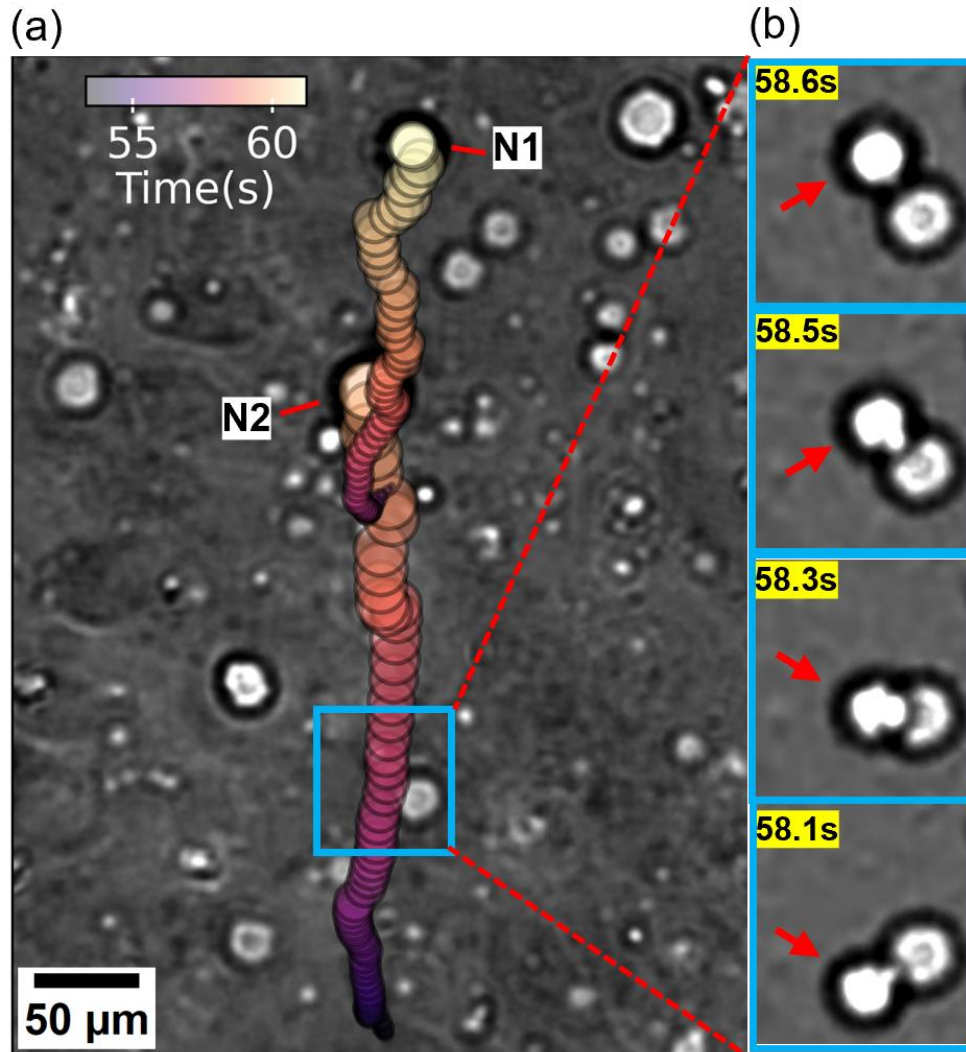
## Findings

- Nodule size is influenced by the location due to local geometric restraint and chemical distribution.
- 1<sup>st</sup> wave nodules tend to nucleate on the dendrite front and have a larger final size.
- 2<sup>nd</sup> wave nodules tend to nucleate between dendrite arms and has a smaller growth rate and growing time.

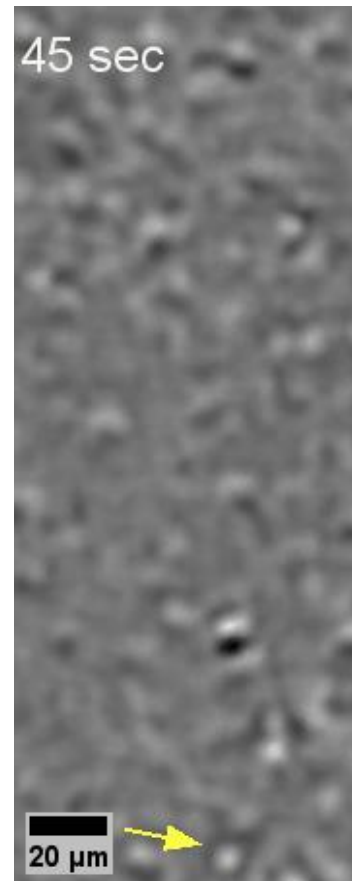


# Floatation

*Floatation can result in inhomogeneous microstructure and cause reduced mechanical properties*



Floatation of N2



## Findings

- The nodules showing floatation are some of the largest nodules.
- Floatation can take place across a range of distances.

## *Content*

### Inoculant Kinetics

- **Distance and Speed**

### Nucleation

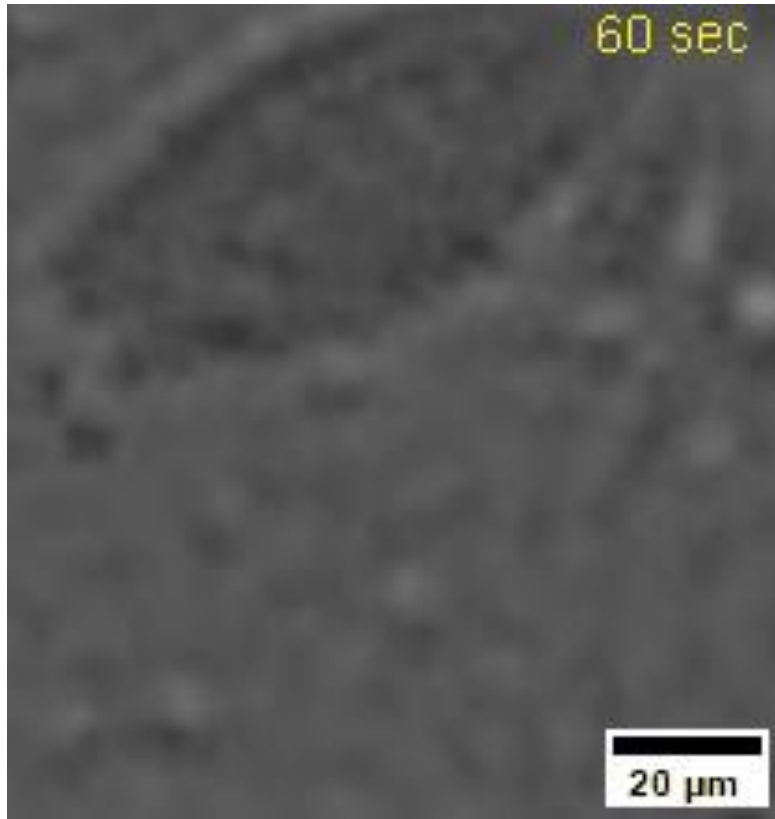
- Three Nucleation Waves
- Spheroidal growth
- Flootation

### ✓ **Degenerate Morphologies**

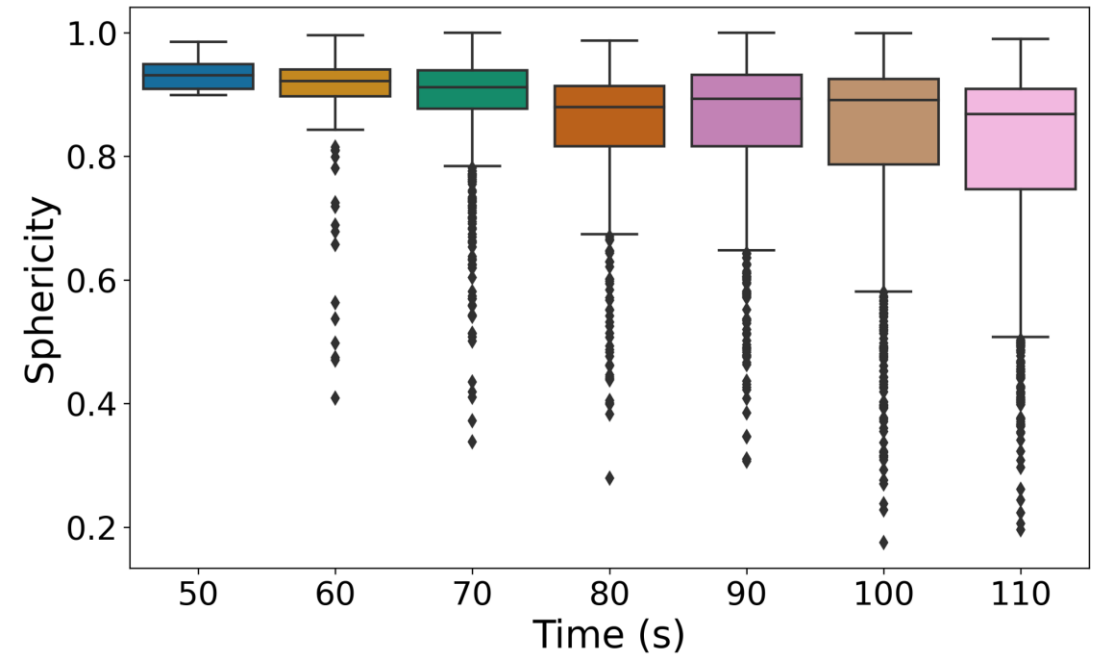
- **Sphericity change**
- **Interconnection**

# Sphericity Change

Example of Sphericity Change Over Time



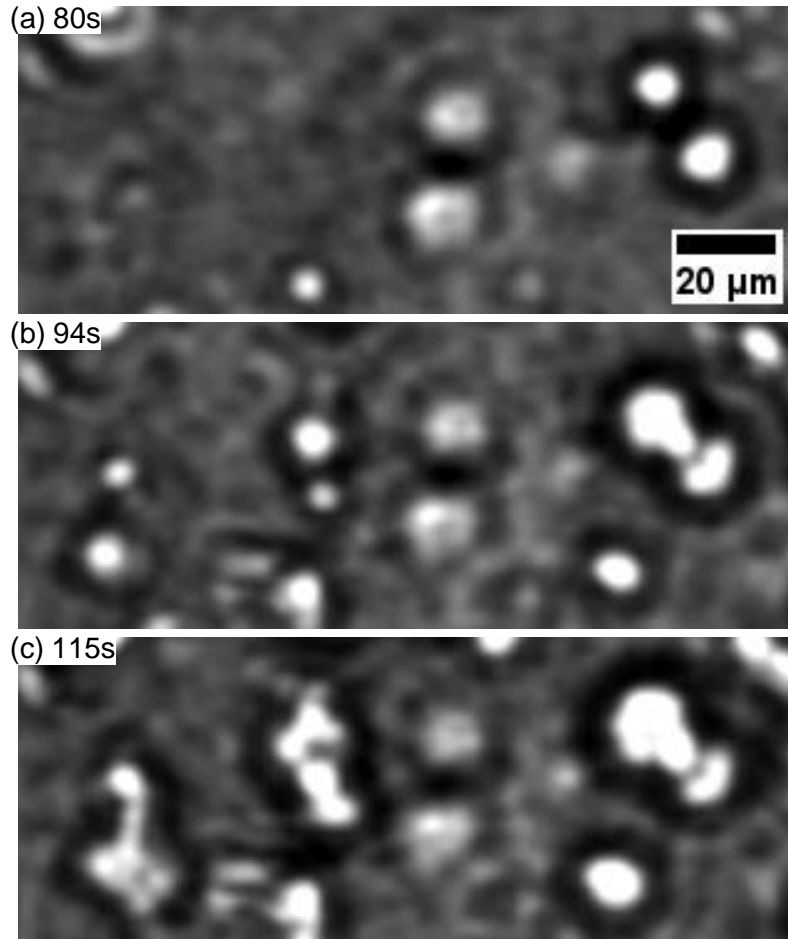
Global Sphericity Every 10 Seconds





# Interconnection

## Interconnection of 3 Pairs of Nodules



### Findings

- Approximately 39.8% of nodules from third nucleation show interconnection during the late stage of solidification, particularly when close nodules are present.

# Conclusion

- **Increasing capability of synchrotron radiation techniques allows observations of highly dynamic processes, which may lead to better understanding of the solidification behavior.**

# Ongoing work

- **Simulation of growth and degenerate of graphite nodule**

## Funding bodies

- Research Fund for Coal and Steel

## Co-authors

David Wigglesworth, S. Nedje, Yasuda Hideyuki, Narumi Taka, Jesper H. Hattel, Jenny Shepherd, Peter D. Lee, and Mohammed Abdul Azeem

## Other support

- Diamond Light Source, especially I12 Team
- Research Complex at Harwell

