

# Nanoprecipitate Evolution in Next Generation Ferritic-Martensitic Steel under Ion Irradiation

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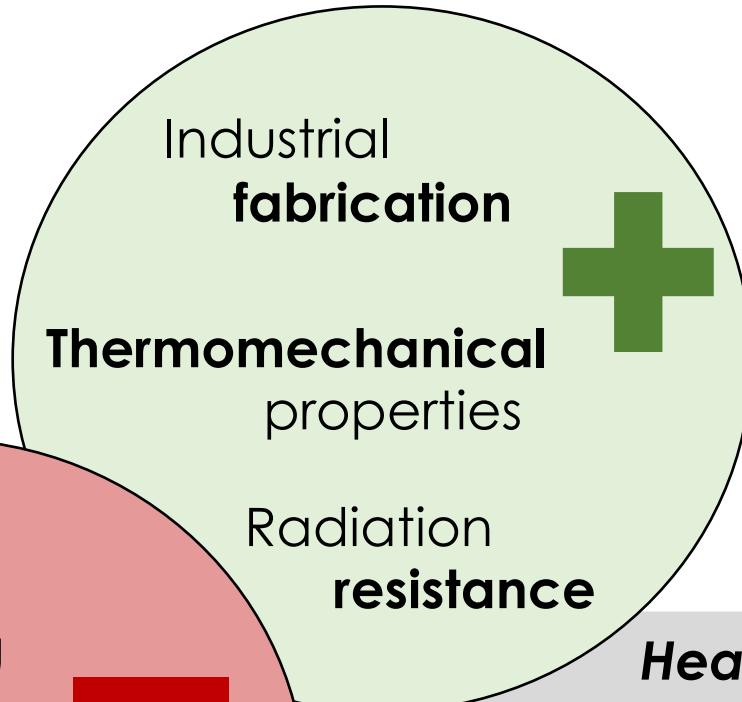
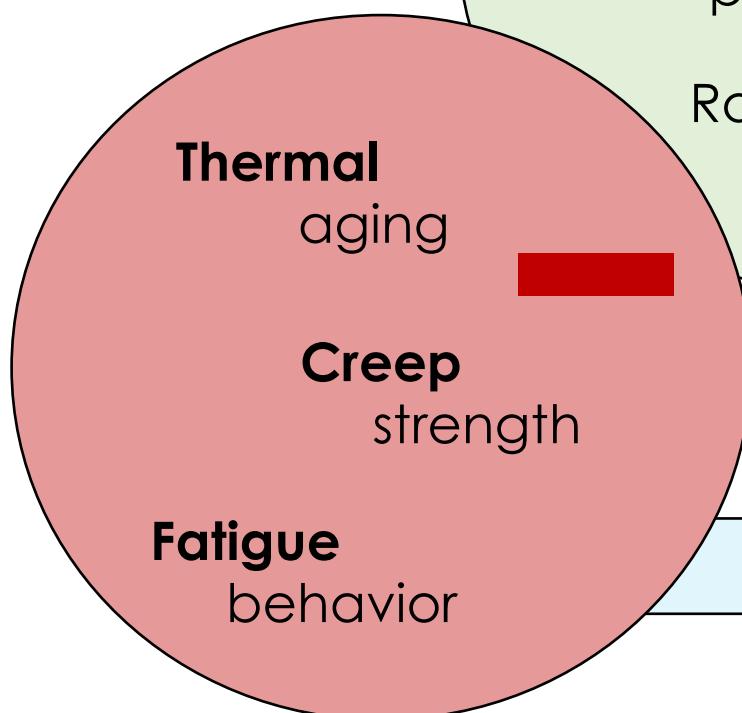
<sup>c</sup> Now at Intel Corporation



# Reduced Activation Ferritic/Martensitic (RAFM) Alloy Development for Fusion Components

## RAFM STEELS

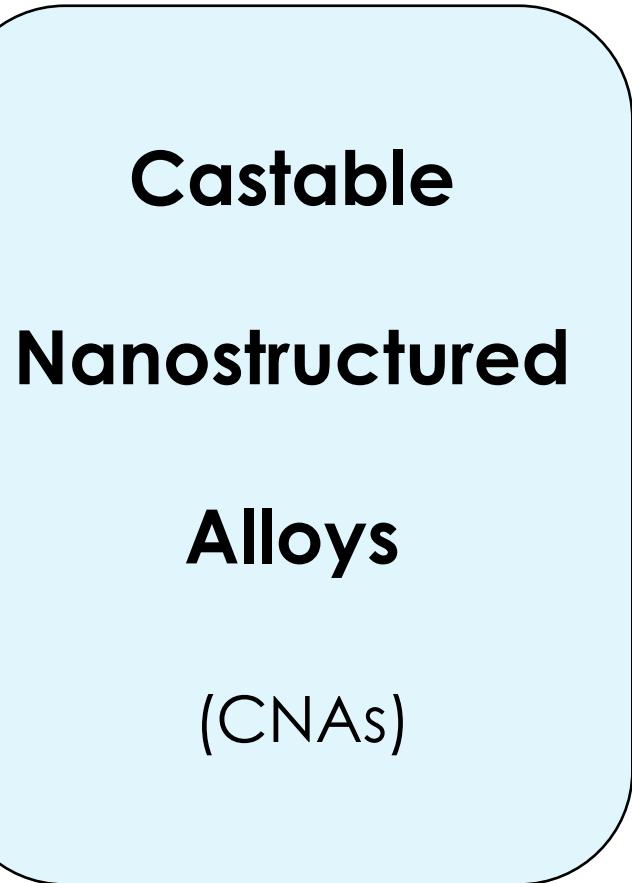
Eurofer97  
F82H



Composition

Heat Treatment

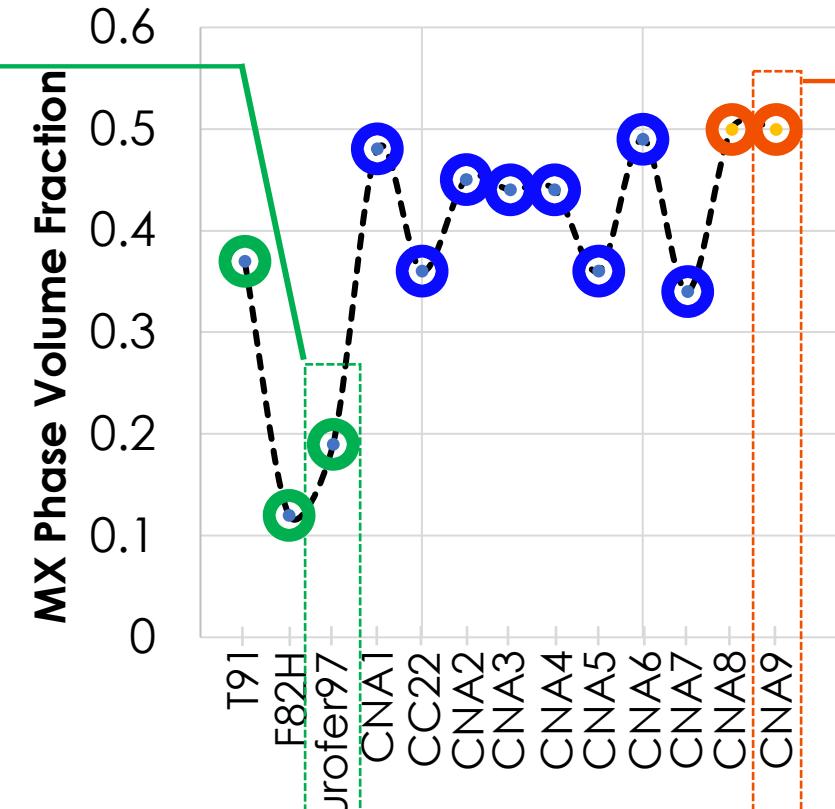
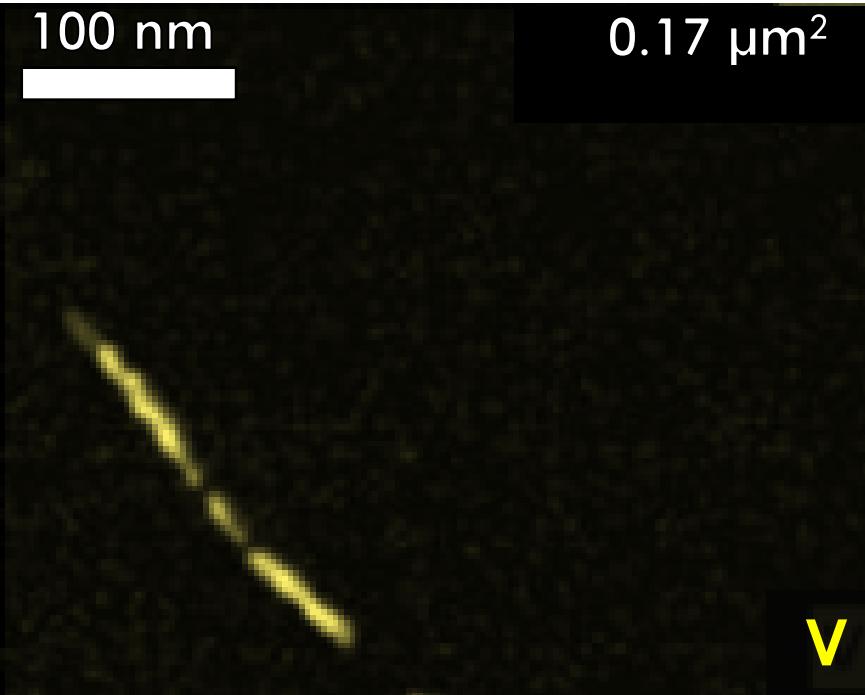
Precipitates



# CNAs : Optimize Precipitation Compared to Traditional RAFM Steels

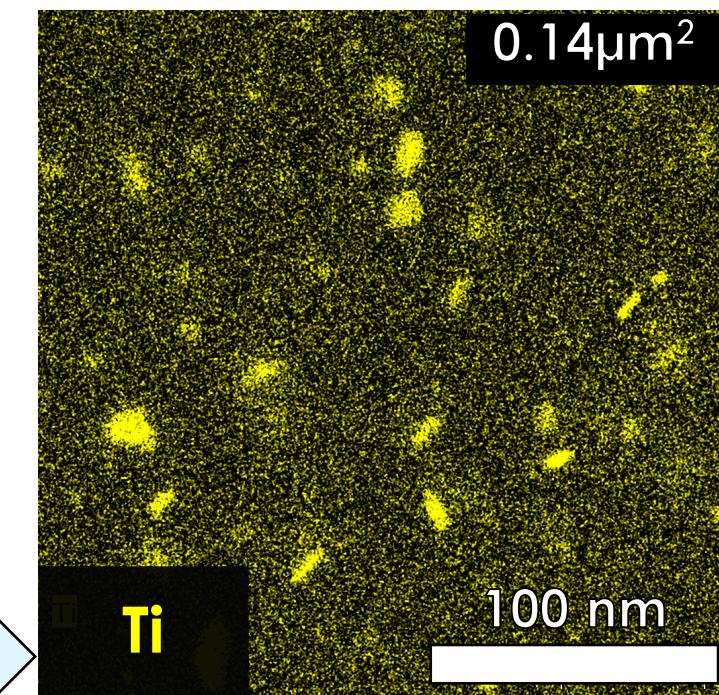
	Eurofer97	CNAs
MX volume fraction	0.2%	0.35% - 0.5%
Typical MX composition	(V, Ta)(C,N)	(Ti,Ta)C

Eurofer97



Optimize Precipitates

CNA9 (Model Alloy)

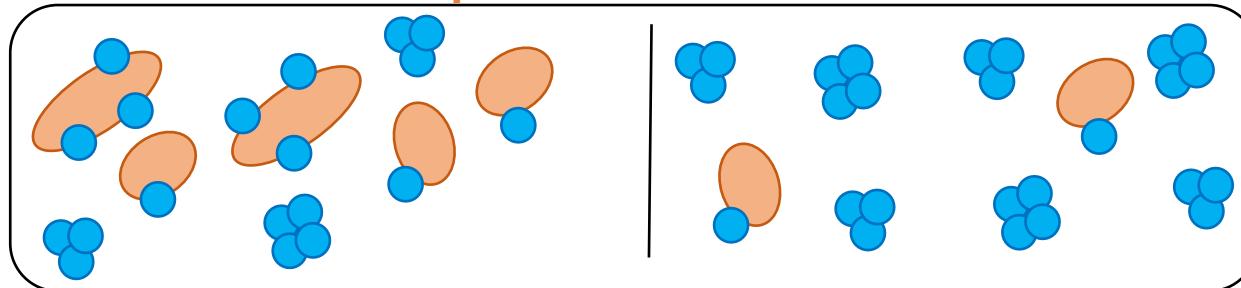


# Why is a high density of precipitates desired?

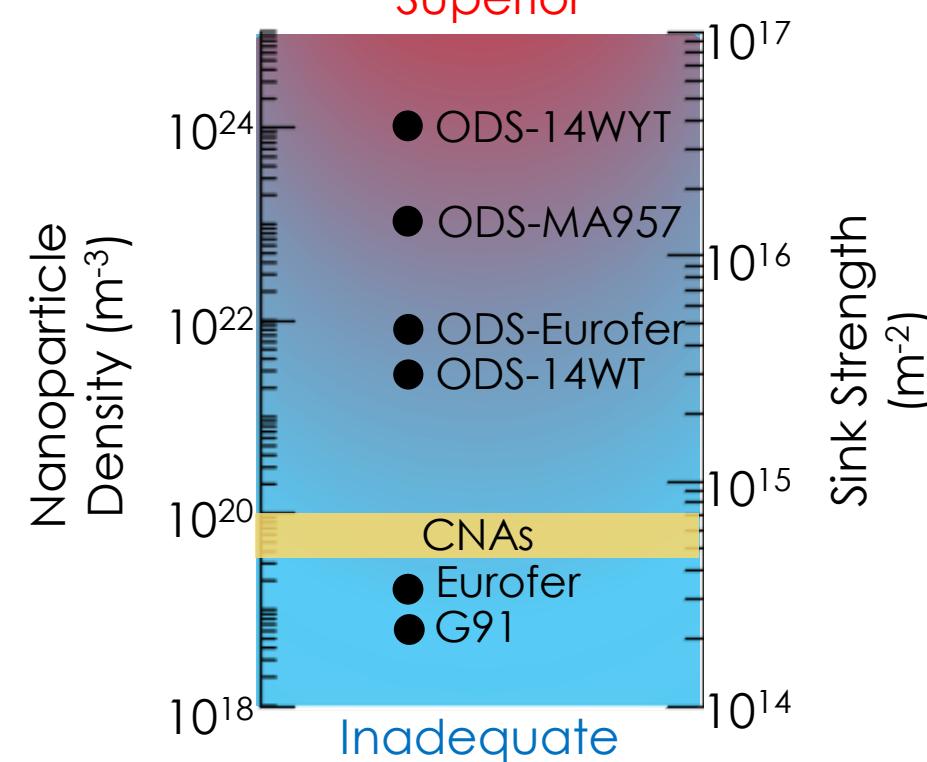
## *Sink strength*

Sinks can sequester He, improving radiation resistance

### Precipitate      Helium



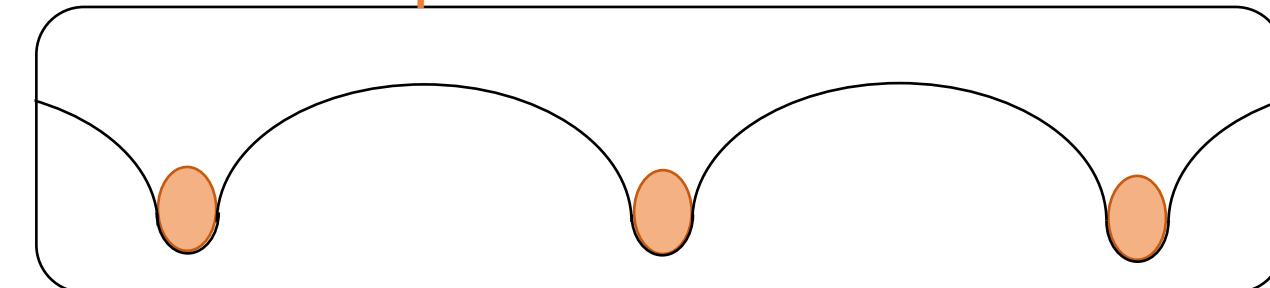
Superior



## *Creep strength*

Precipitates pin dislocations at high temperature

### Precipitate      Dislocation



## This research aims to:

- Study the evolution of nanoprecipitates in CNA9
- Study precipitate-helium interactions

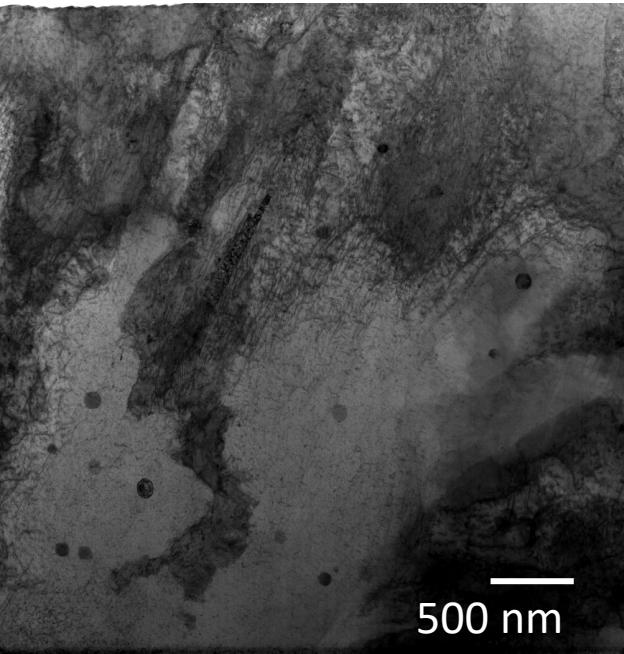
## Hypothesis:

- Precipitate evolution will vary as a function of He
- Precipitates will sequester He atoms

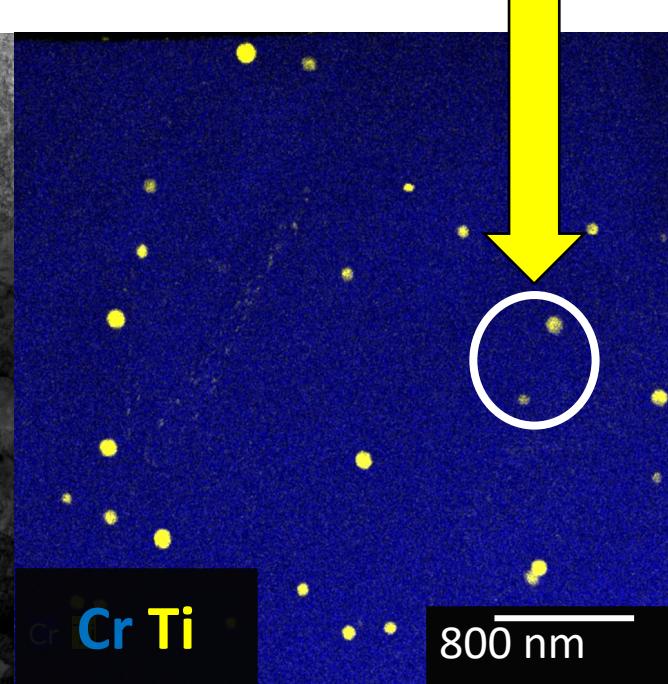
# Model CNA9

CNA9	Fe	Cr	W	Mn	Si	Ta	Ti	V	C
Bal.	8.69	1.03	0.52	0.14	0.09	0.14	0.14	0.05	0.05

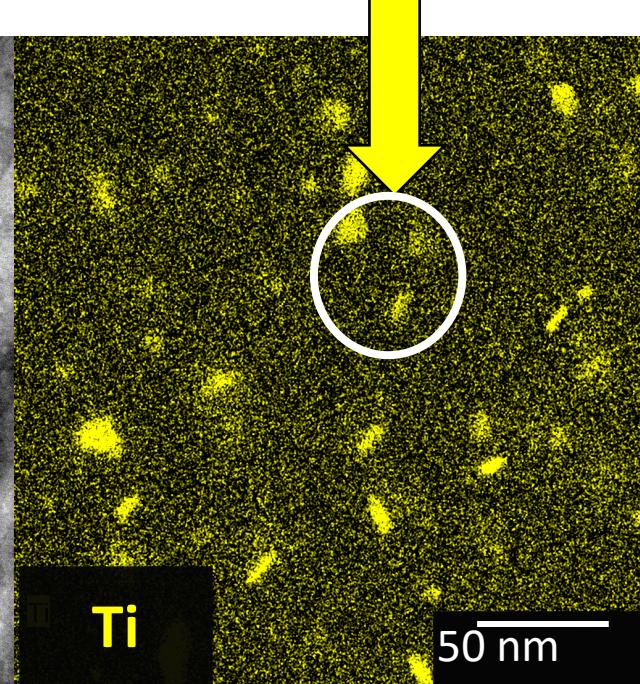
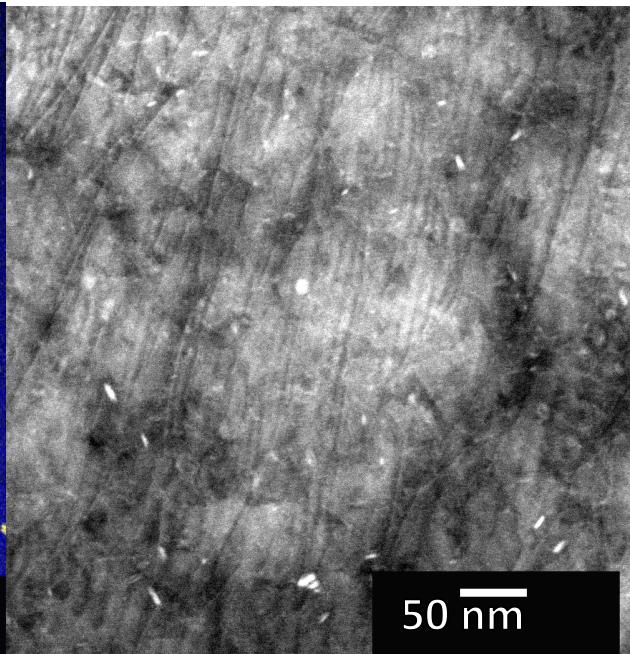
No  $M_{23}C_6$  precipitates



Large circular TiC precipitates (~100nm)



Small MX-type TiC precipitates (2-15 nm)  
heterogeneously dispersed in the matrix



Data courtesy of Tim Graening (ORNL)

# Single effect ion irradiation experiments to study the evolution of nanoprecipitates and helium in CNA9

$1 \times 10^{-4}, 7 \times 10^{-4}$  dpa/s

Dose Rate

Dose

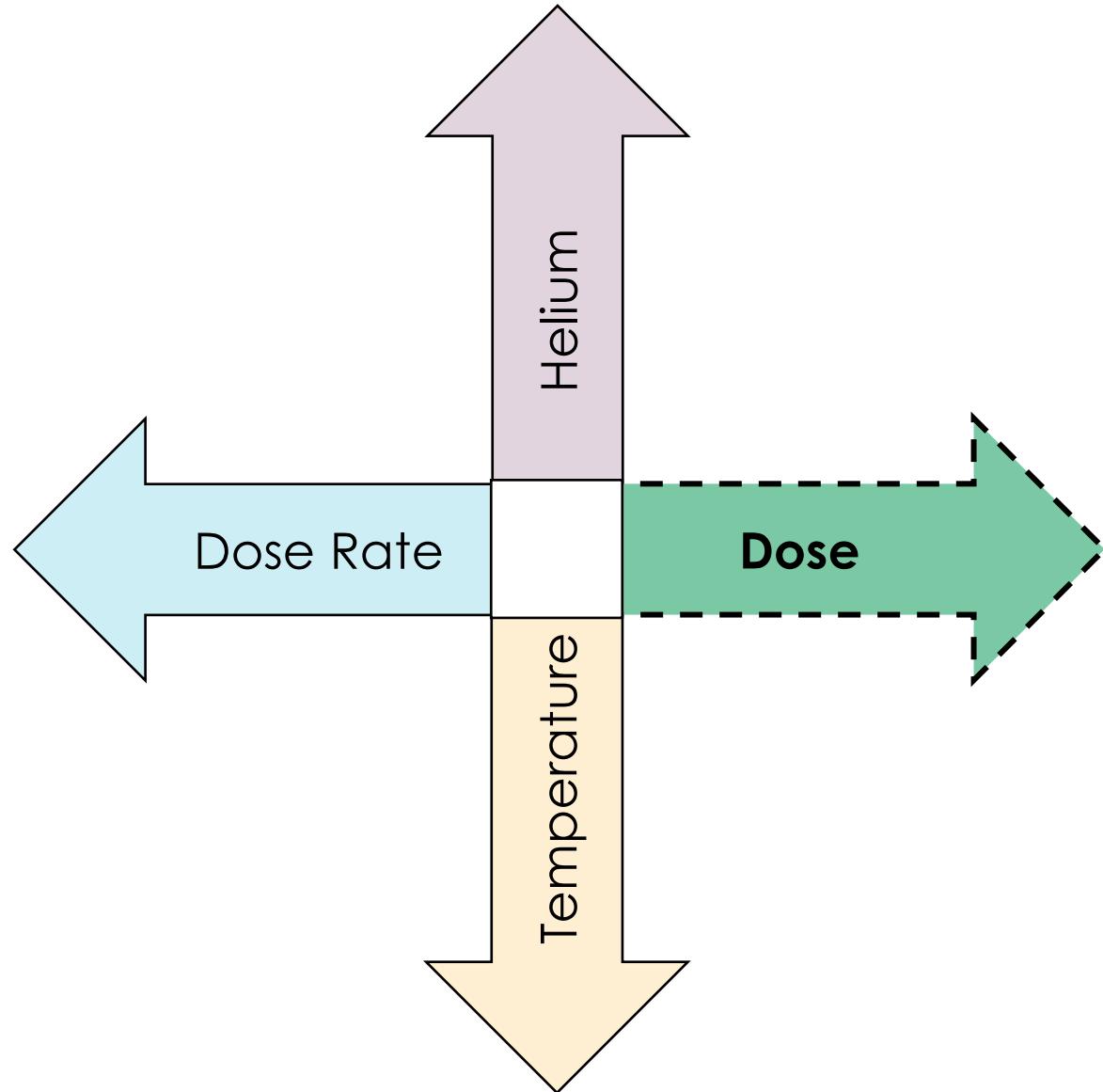
1-100 dpa

0-10 appm He/dpa

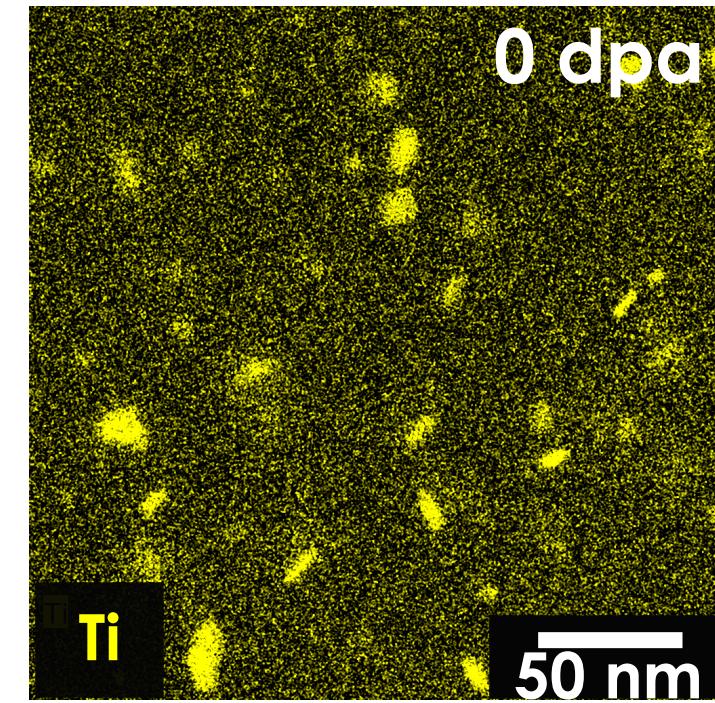
300-600°C

Helium

Temperature



How do the pre-existing TiC nanoprecipitates in CNA9 change as a function of DOSE under ion irradiation?

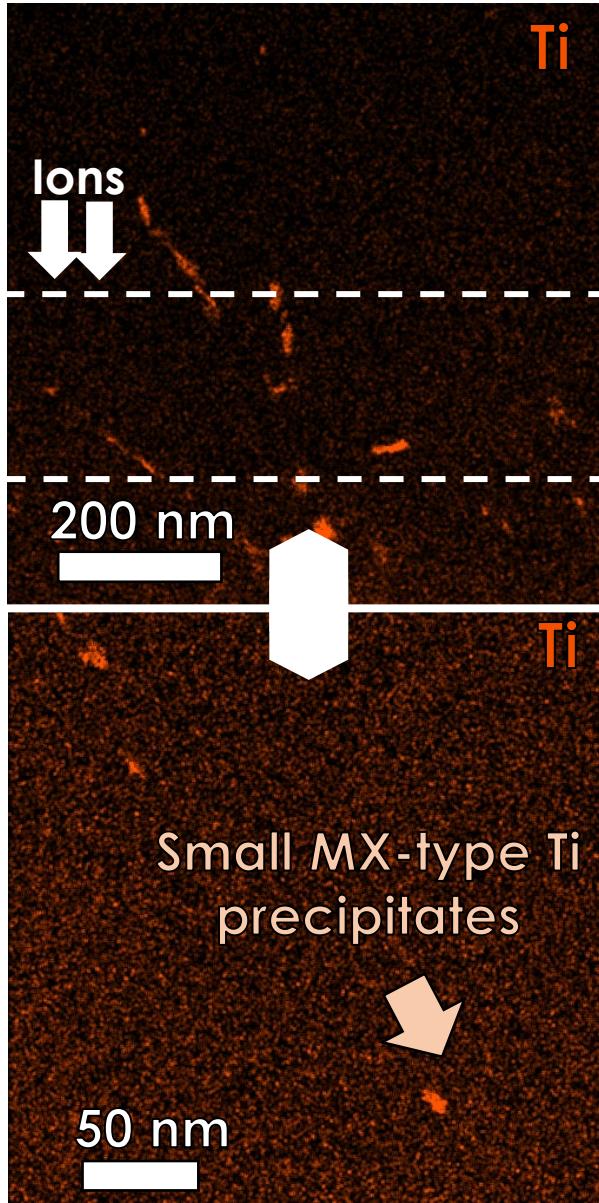


1 dpa

5 dpa

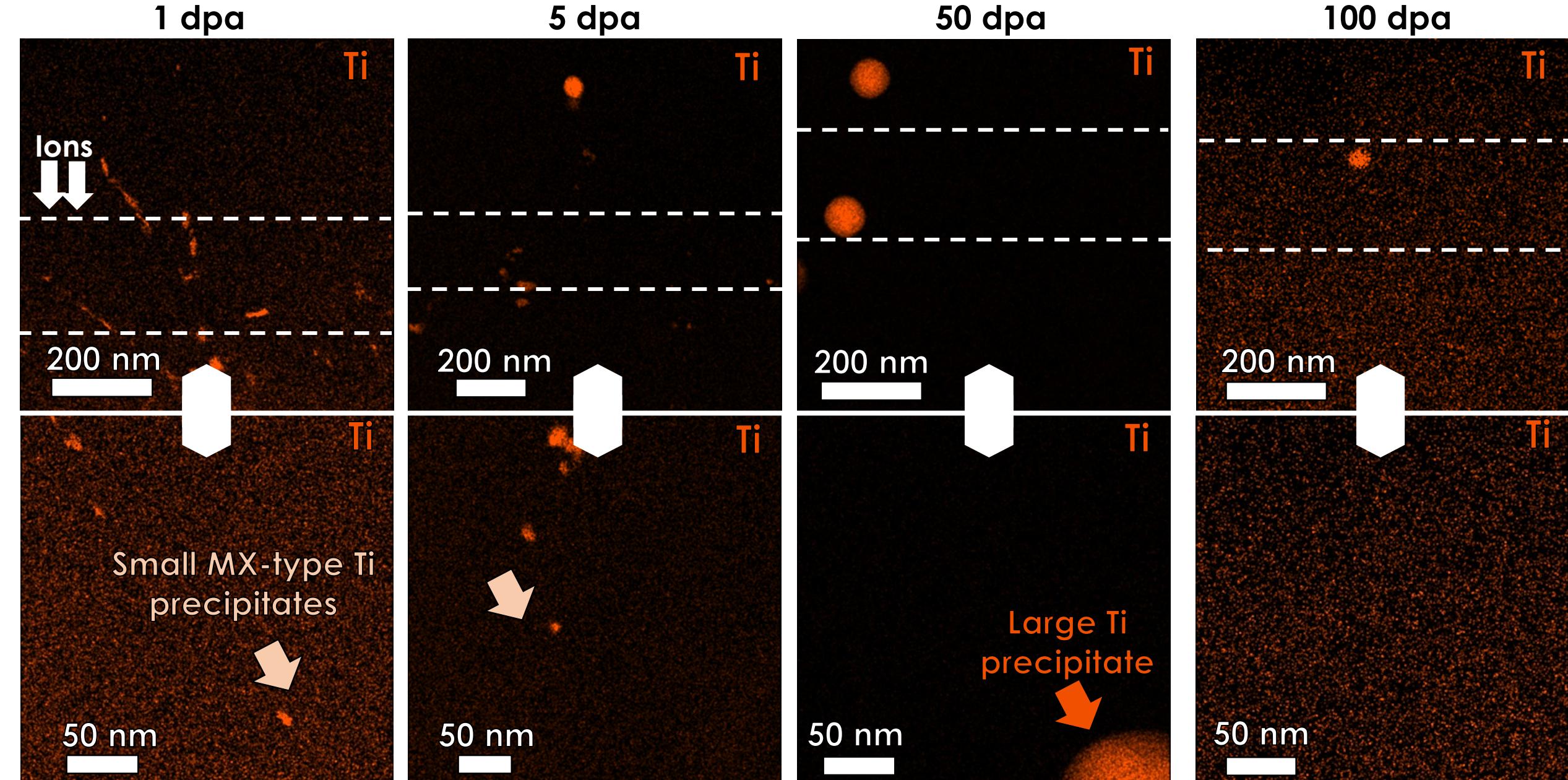
50 dpa

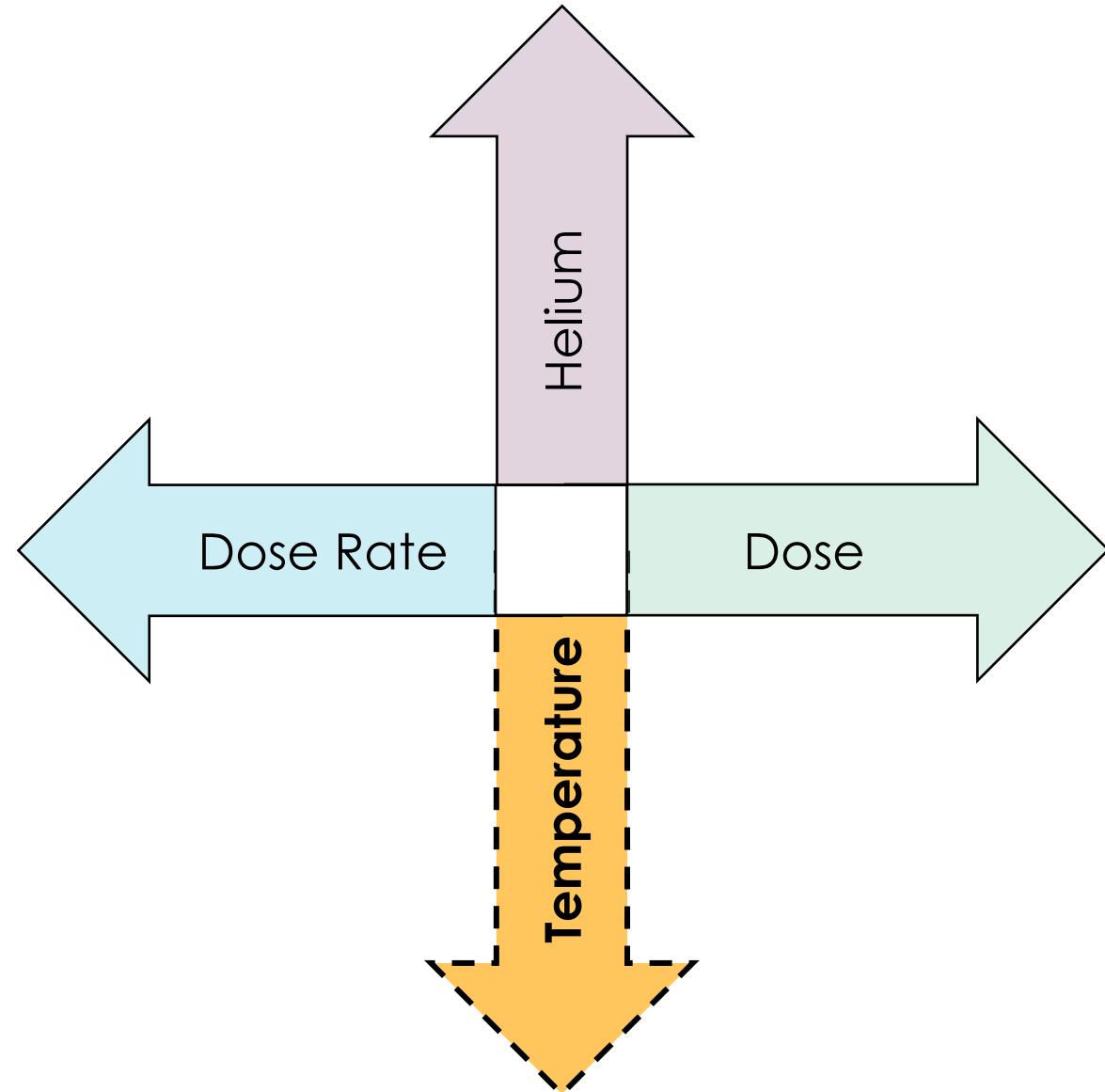
100 dpa





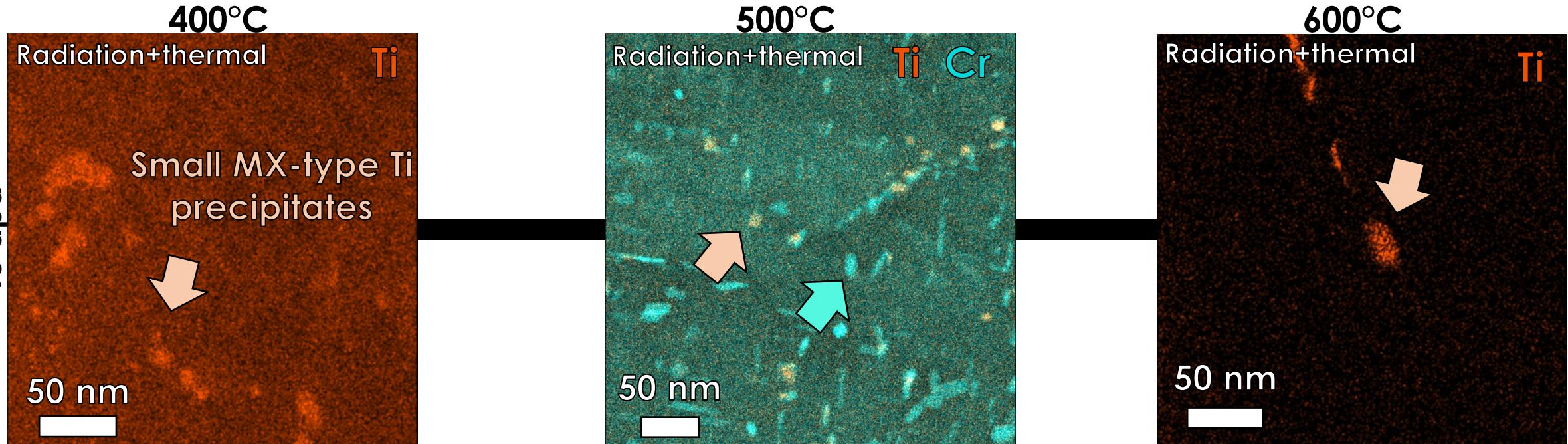
As dose increased, small MX-type TiC precipitates ballistically dissolved but large TiC precipitates remained stable







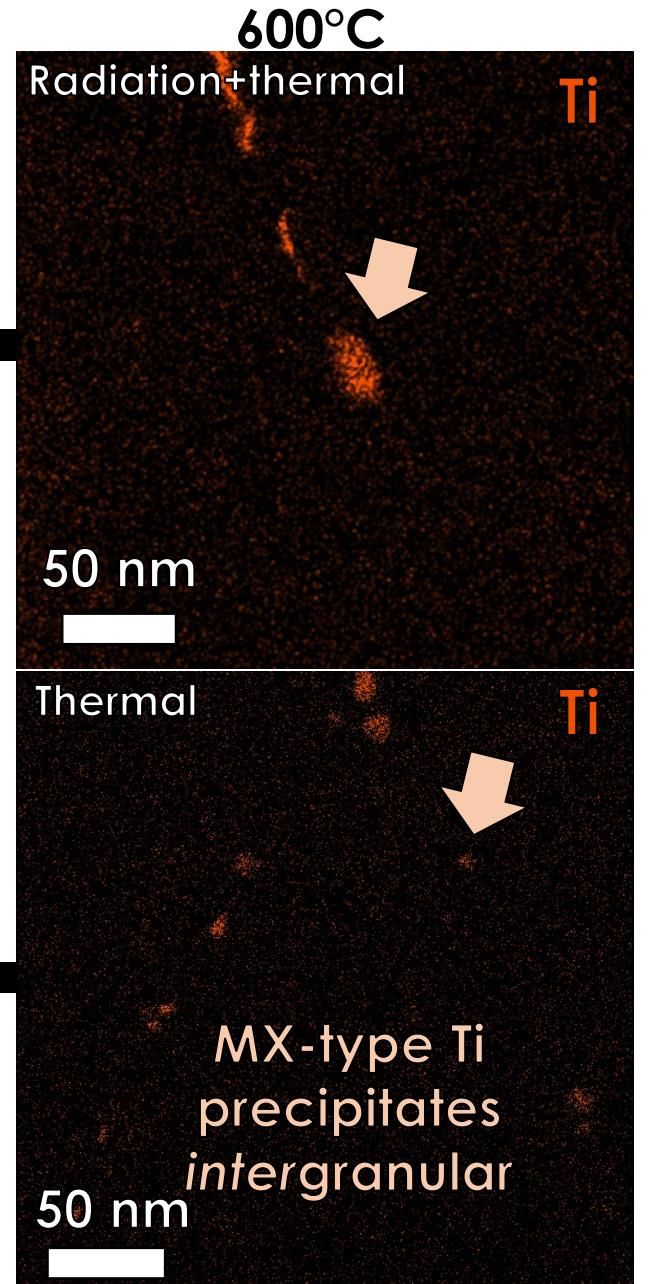
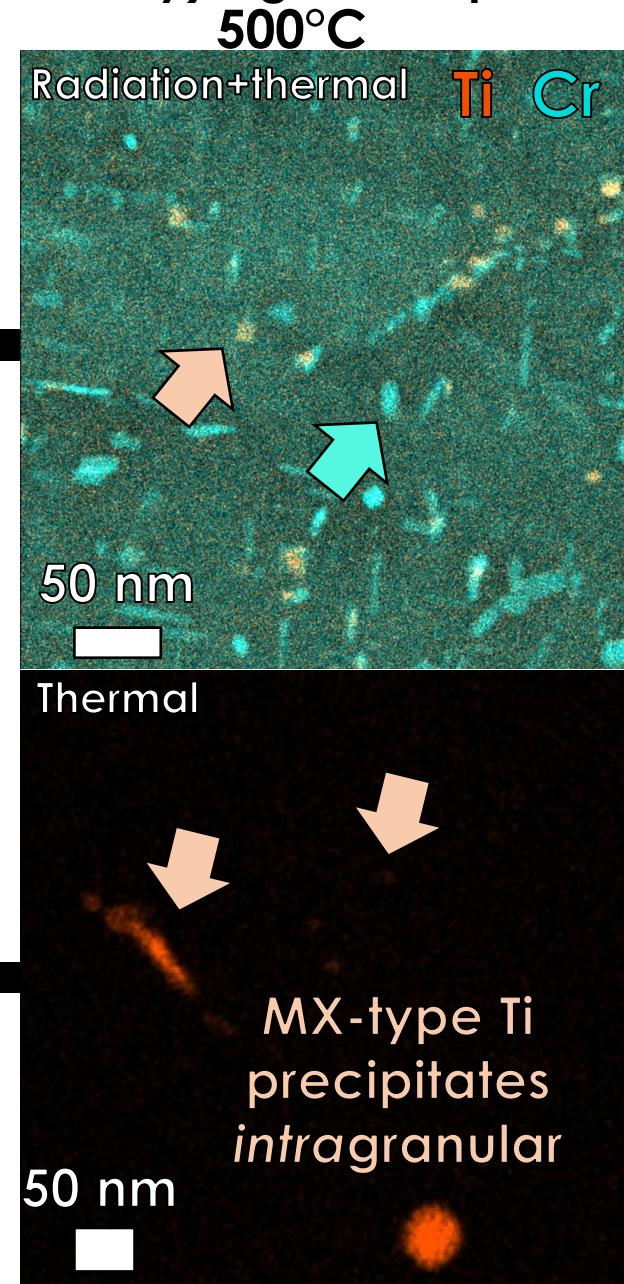
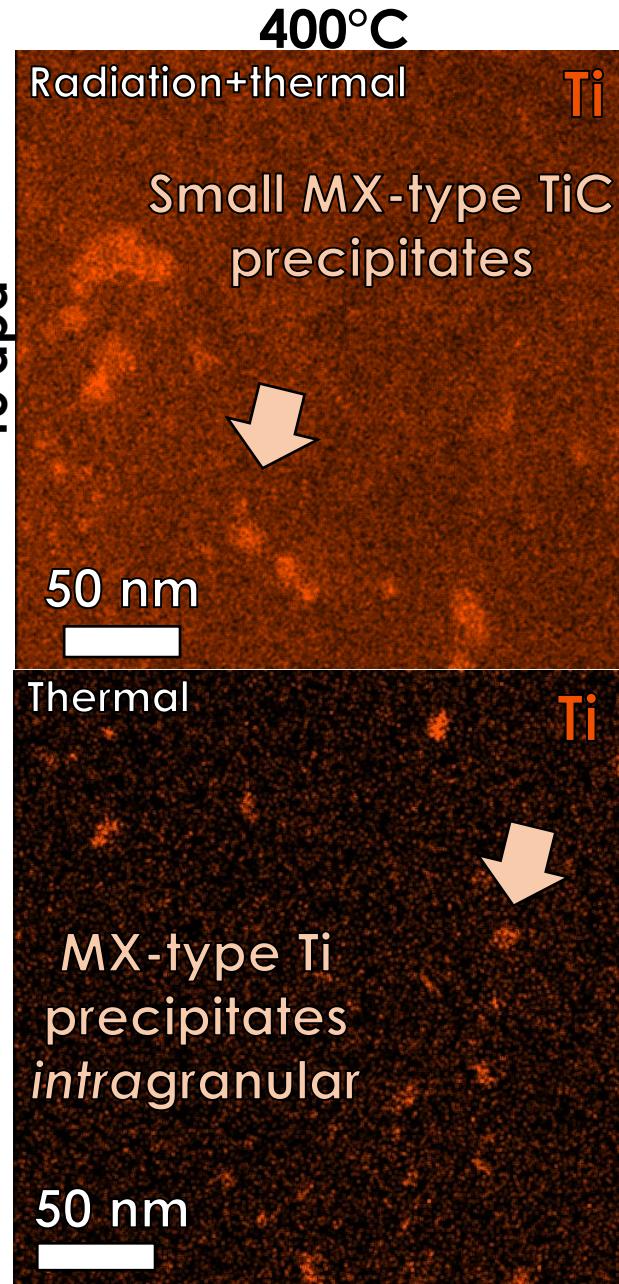
Nominal damage region



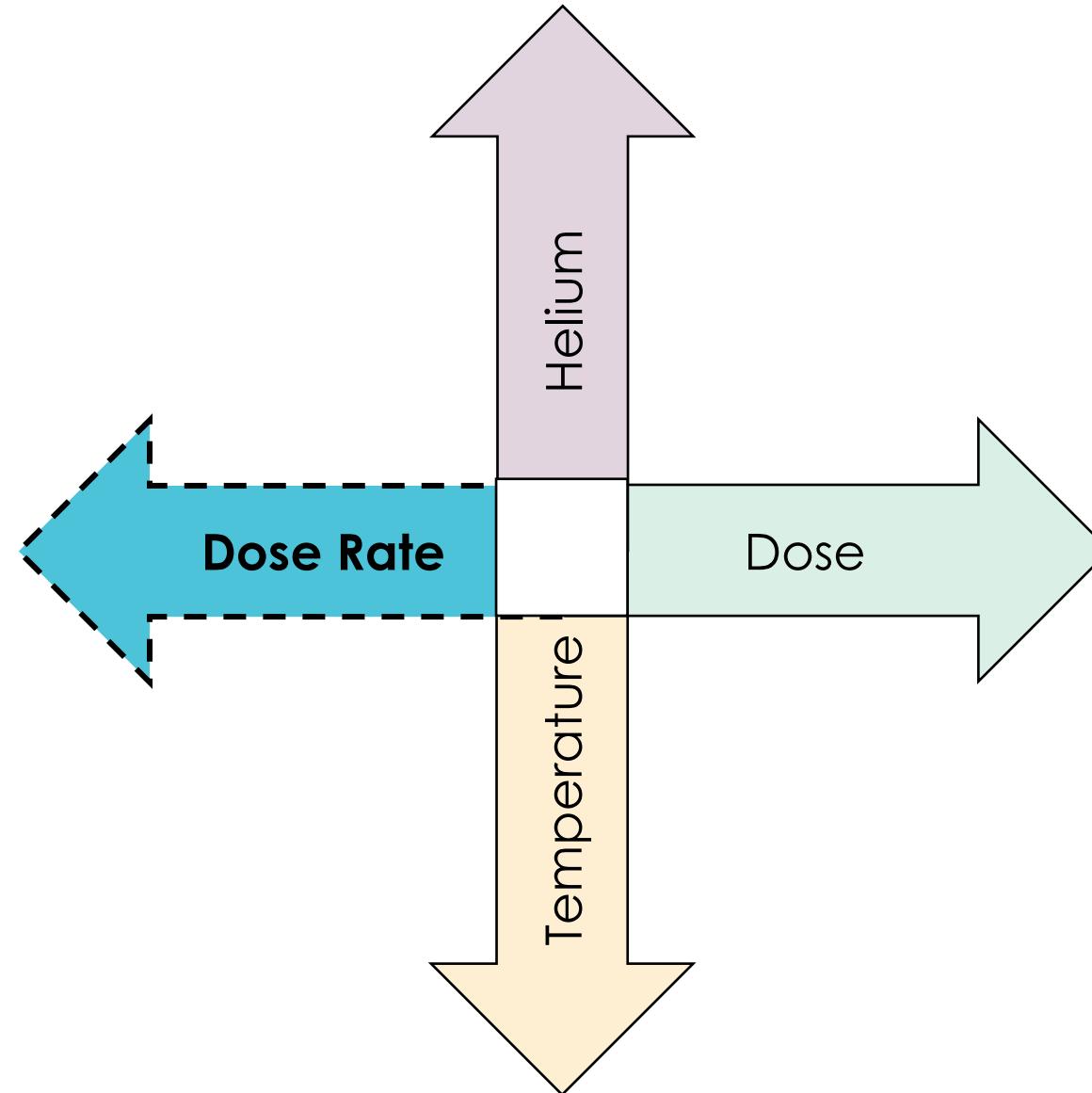
TEMPERATURE SERIES:  $7 \times 10^{-4}$  dpa/s, 15 dpa

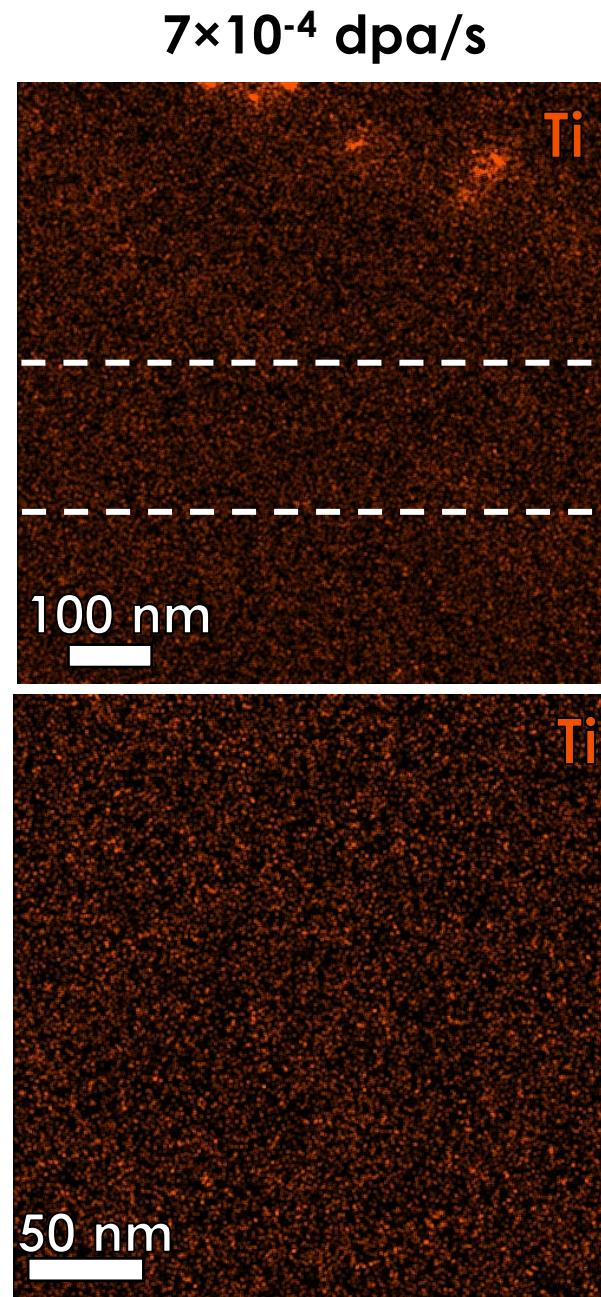
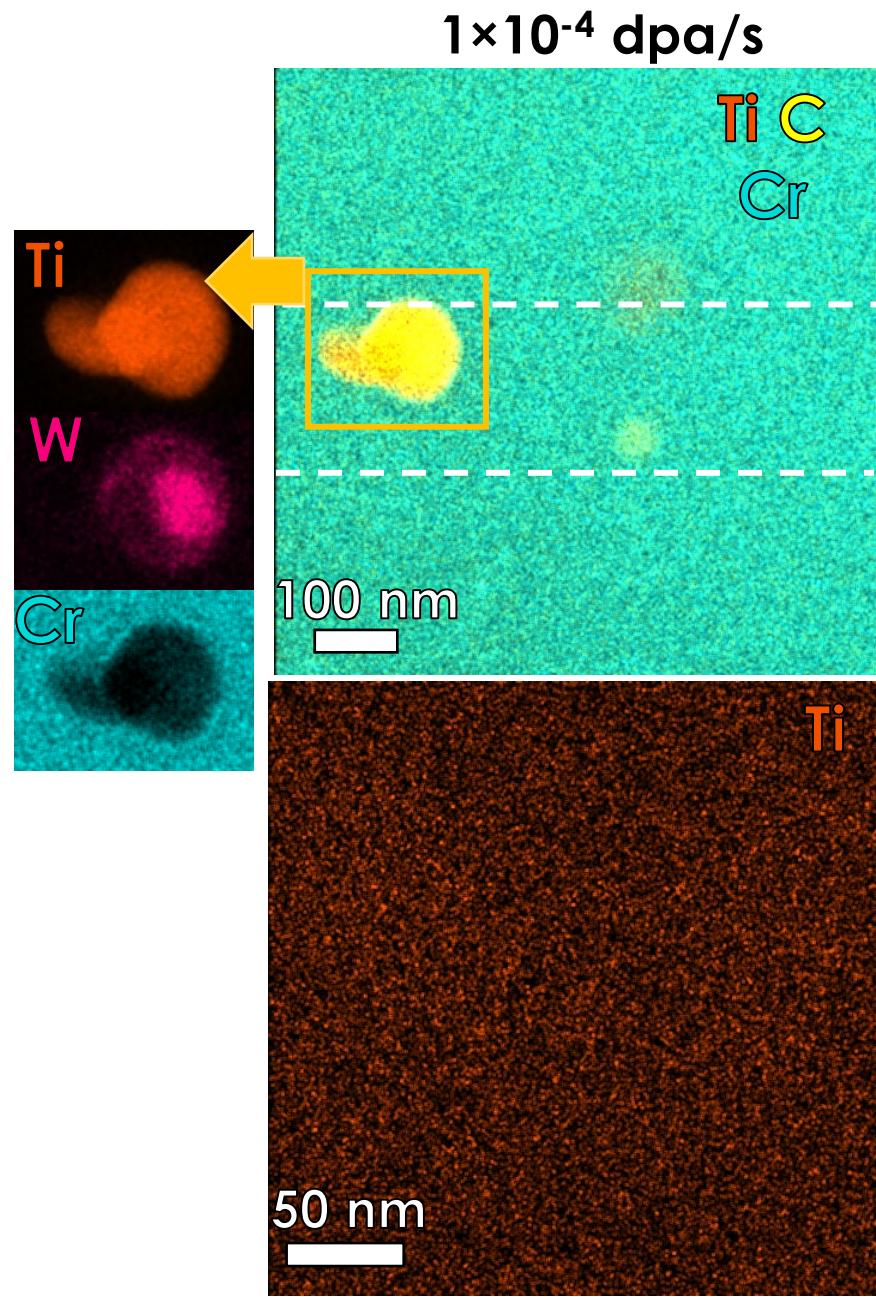
 MX-type TiC precipitates are stable intragranular at (relatively) lower temperatures and stable intergranular at (relatively) higher temperatures

Nominal damage region  
Past implantation depth



TEMPERATURE SERIES:  $7 \times 10^{-4}$  dpa/s, 15 dpa

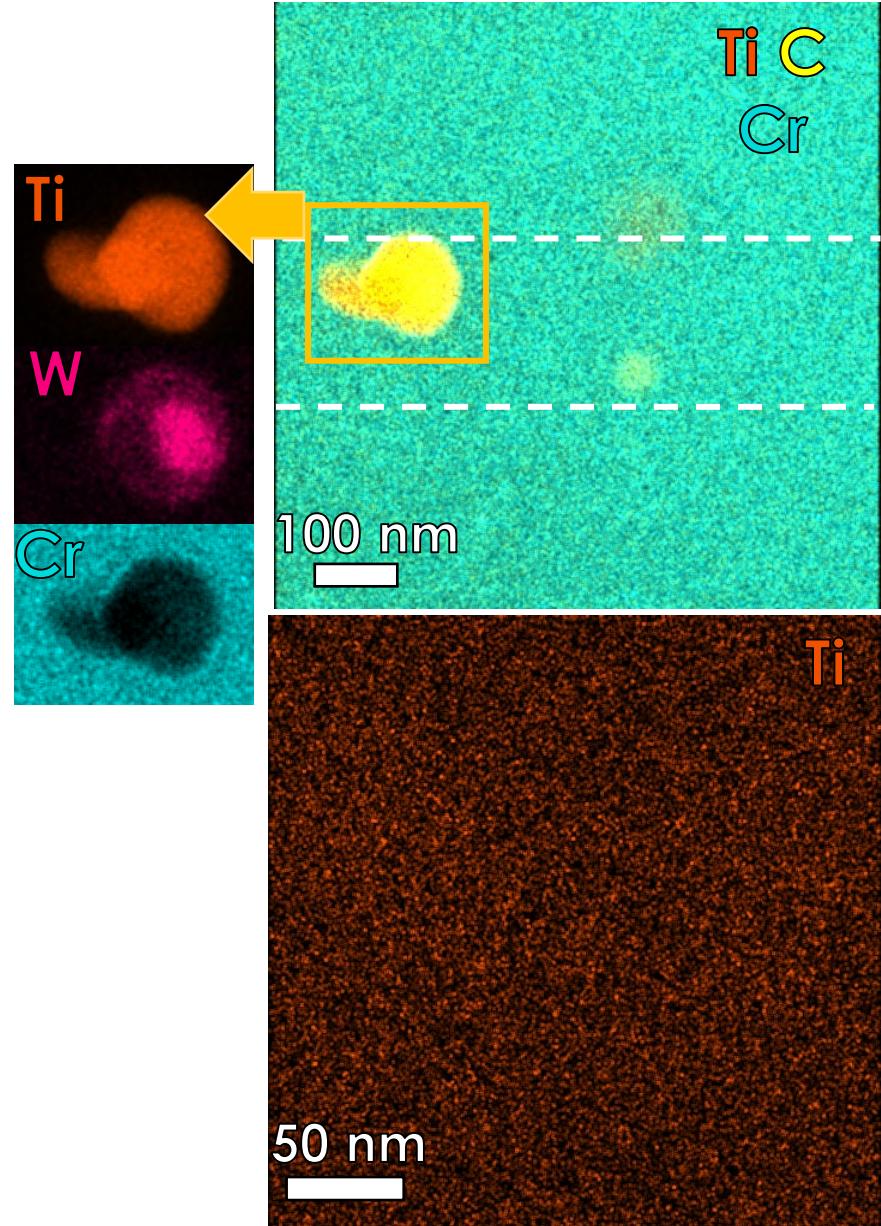




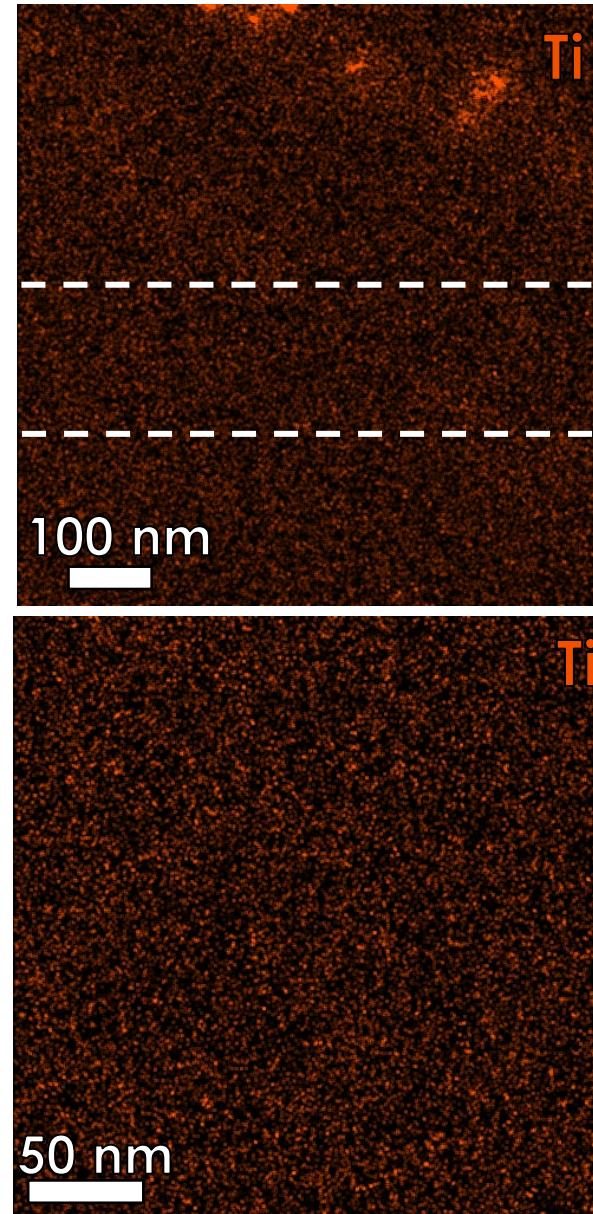
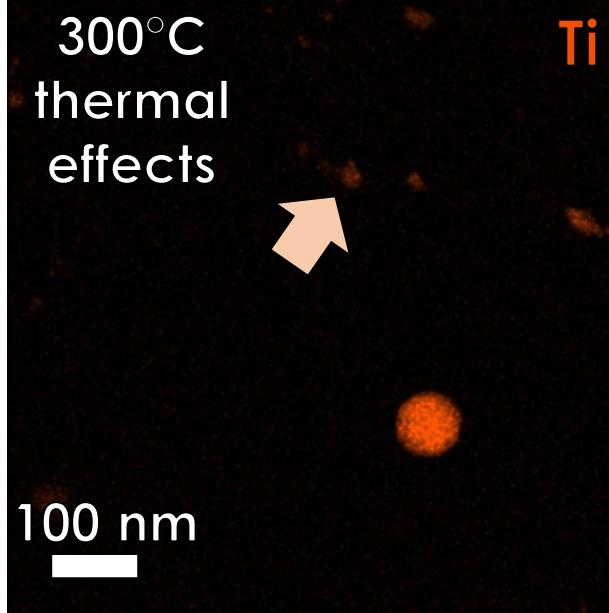


At 300°C, dose rate has no effect but dose and thermal effects dominates

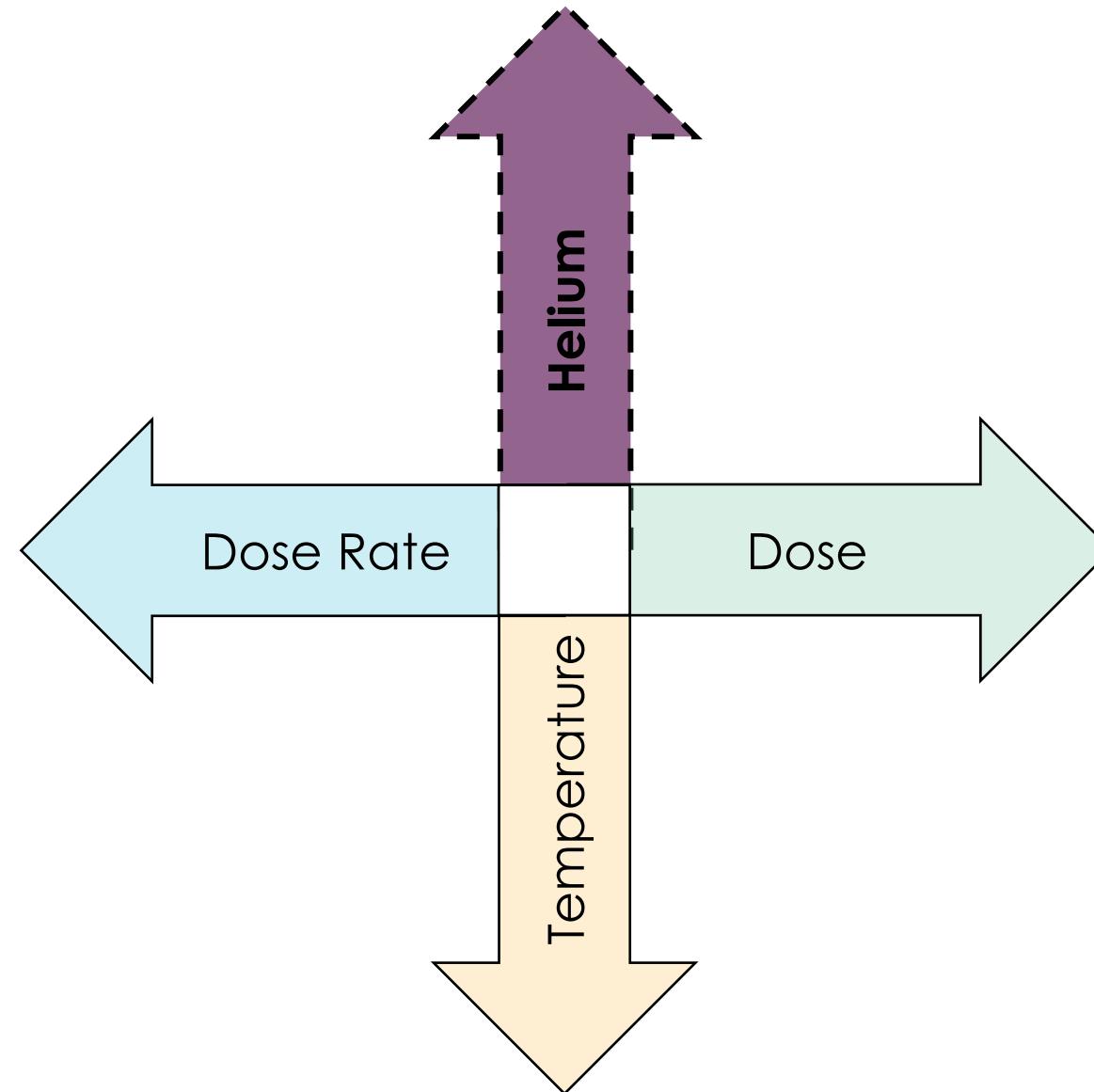
$1 \times 10^{-4}$  dpa/s



300°C  
thermal  
effects



DOSE RATE SERIES: 300°C, 50 dpa





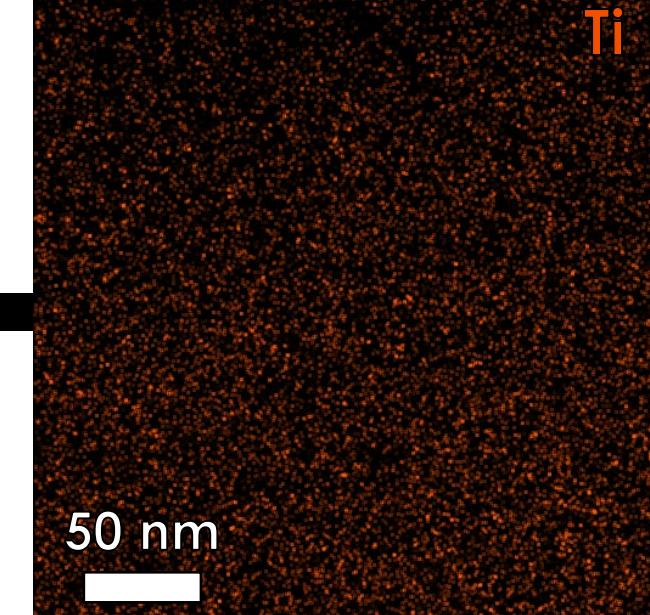
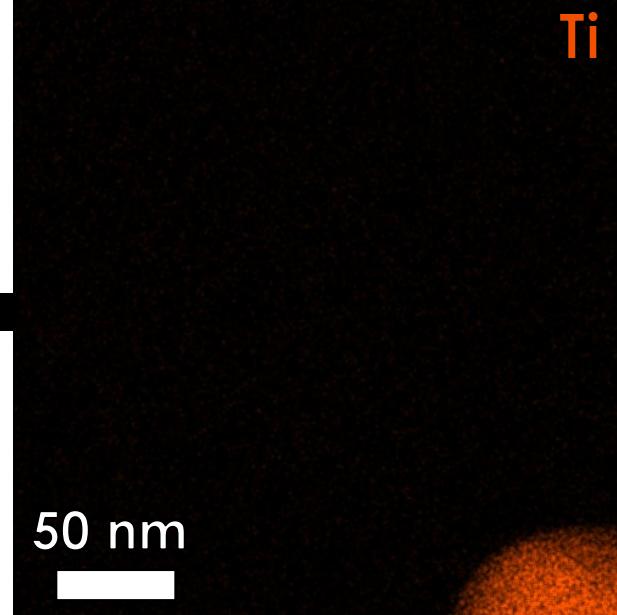
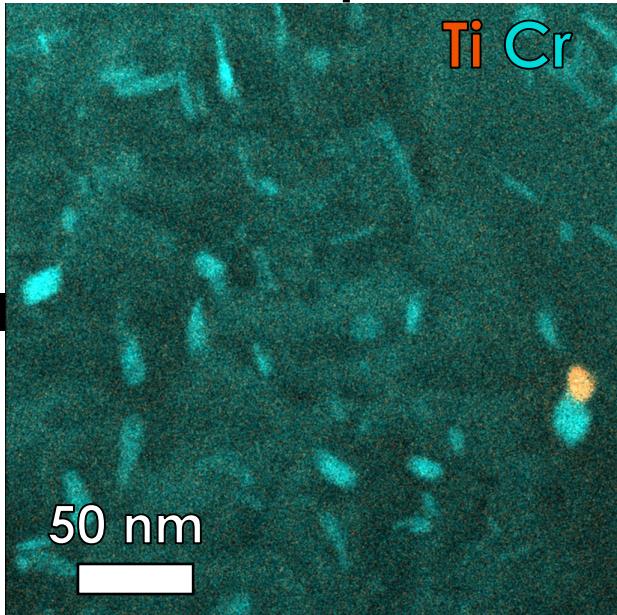
For a given temperature, dose effect dominates over helium effects

15 dpa

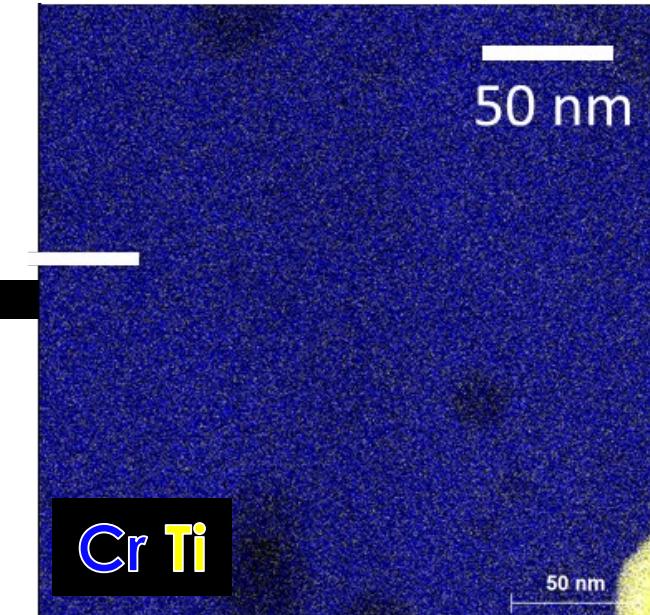
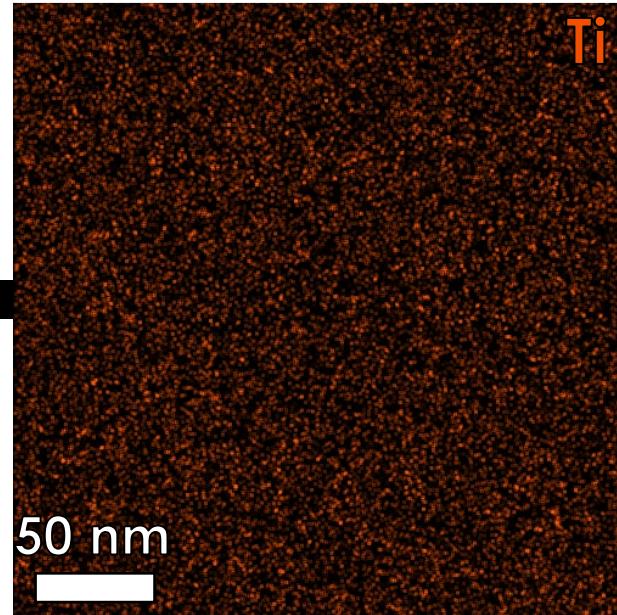
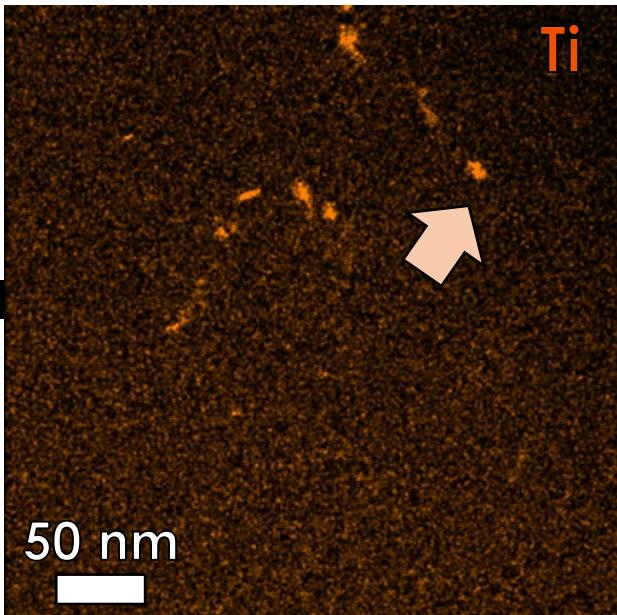
50 dpa

100 dpa

No Helium



10 appm He/dpa



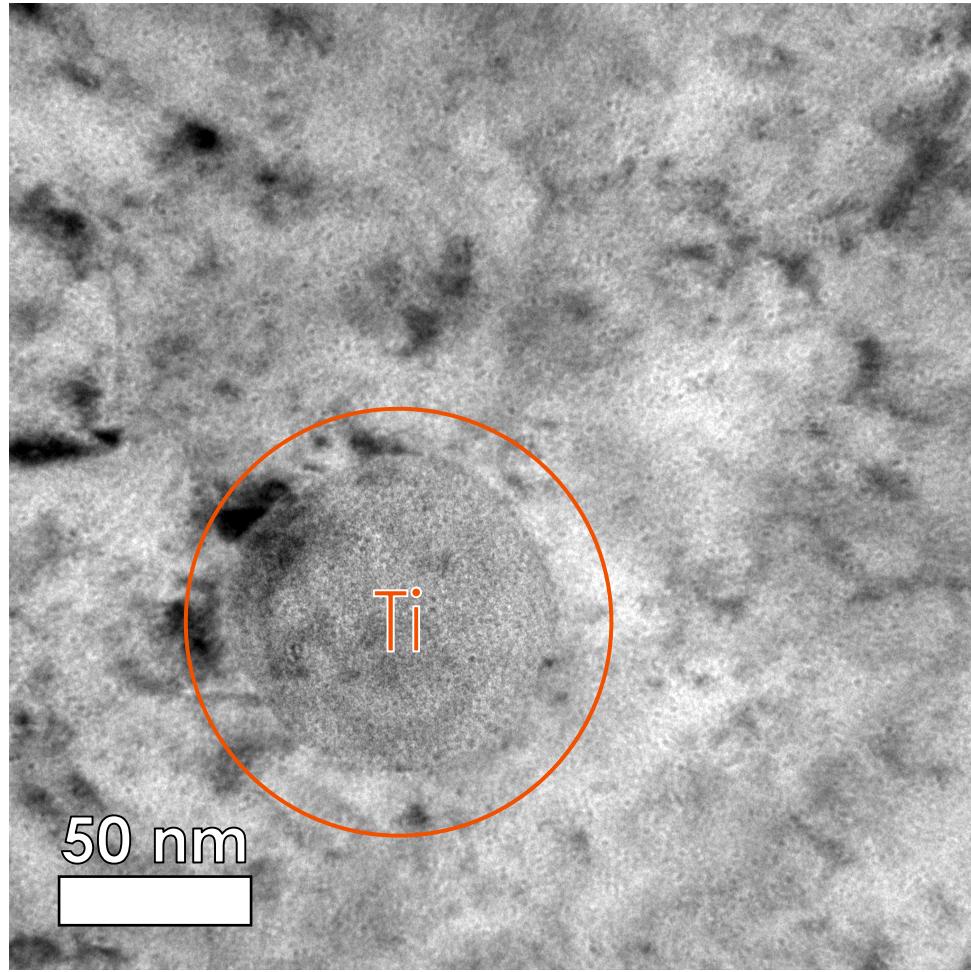
500°C,  $7 \times 10^{-4}$  dpa/s, 10 appm He/dpa

Dual 100 dpa: Tim Graening

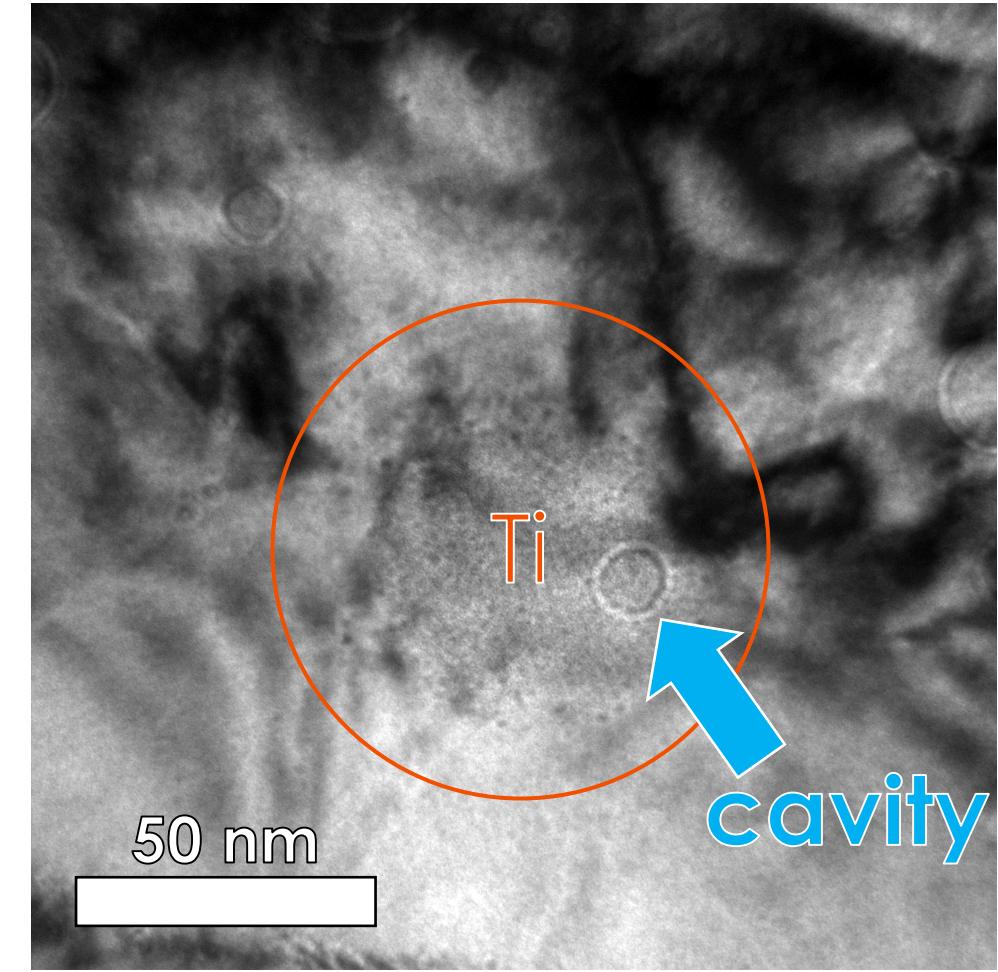


## Stable large Ti-bearing precipitates display He trapping ability

0 appm He/dpa

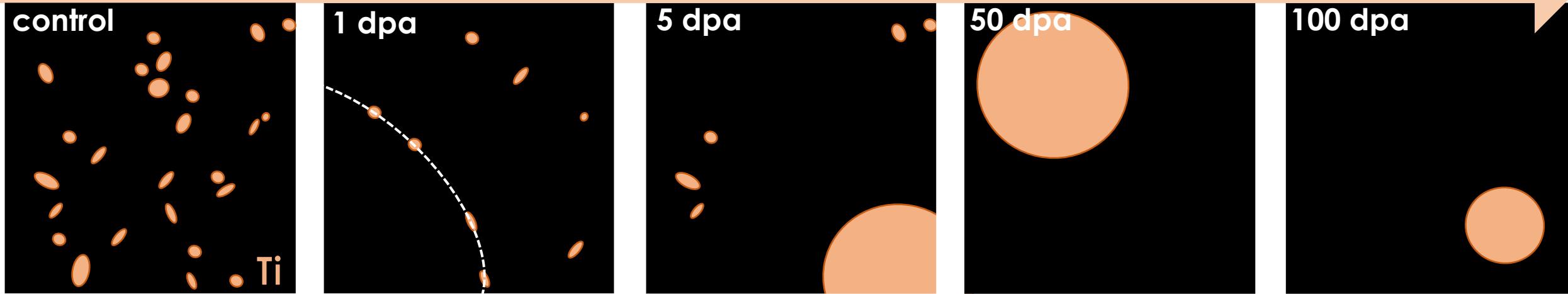


10 appm He/dpa



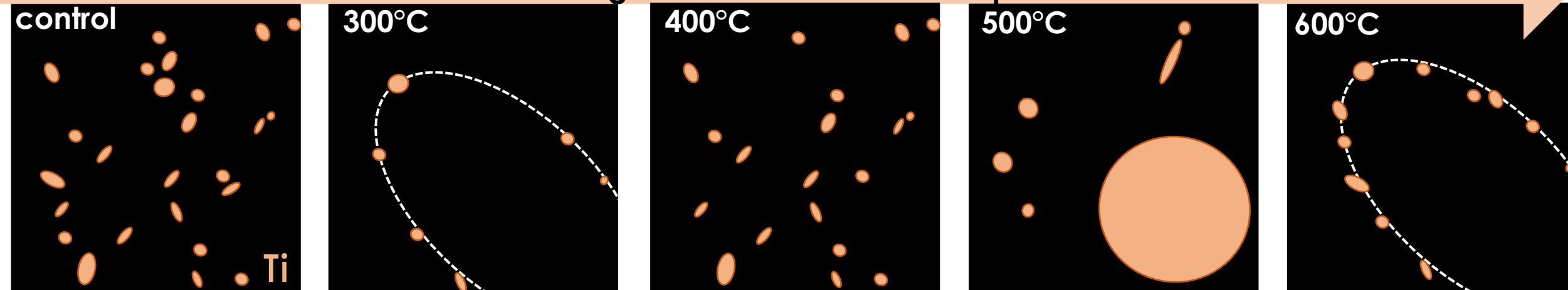
## DOSE EFFECT

As dose increased, MX-type Ti precipitates ballistically dissolved but large Ti precipitates remained stable



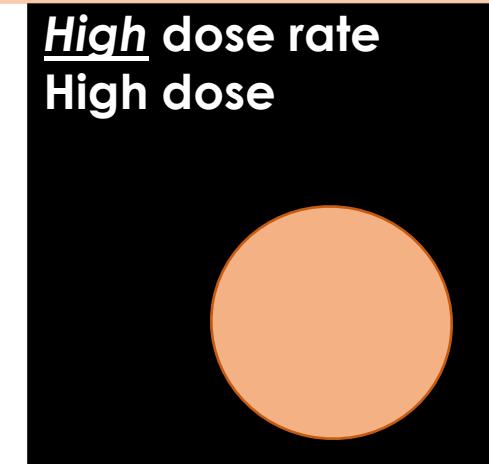
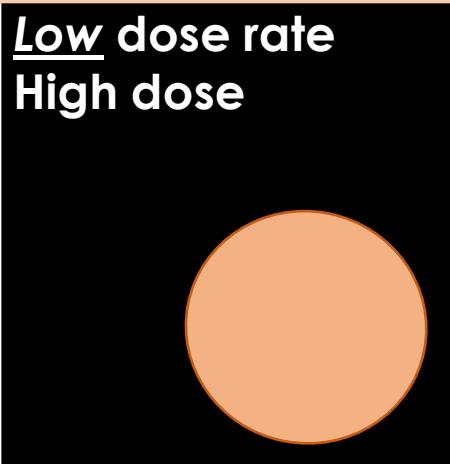
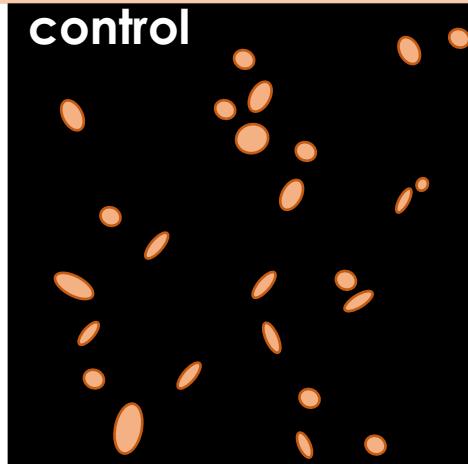
## THERMAL AGING EFFECT

MX-type TiC precipitates are stable on grain boundaries at (relatively) low and high temperatures but stable within grains at intermediate temperatures



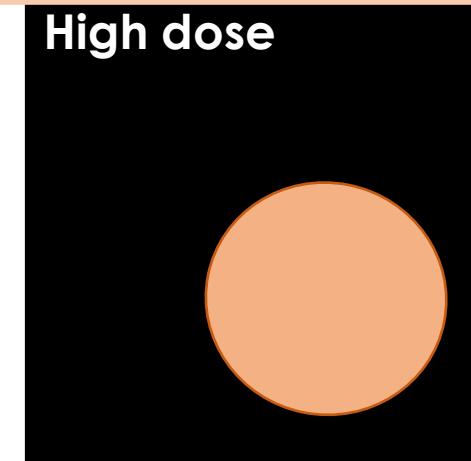
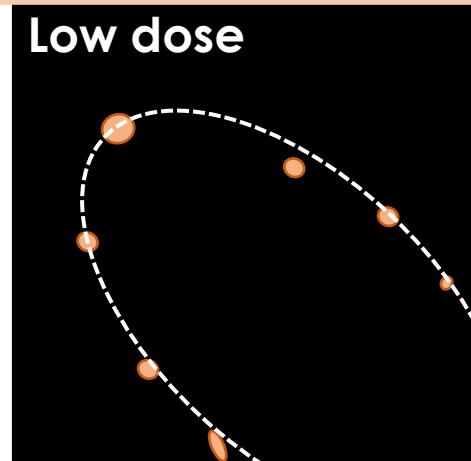
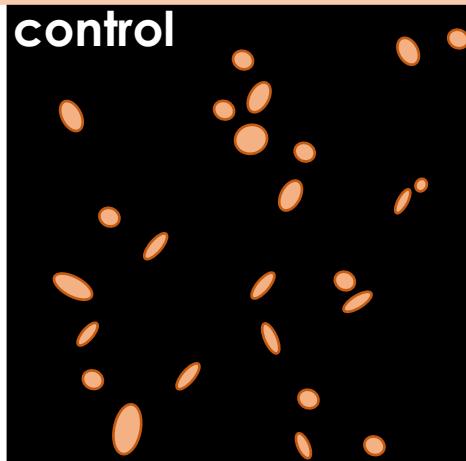
# DOSE RATE EFFECT

At 300°C, dose and thermal effects dominate over dose rate effects



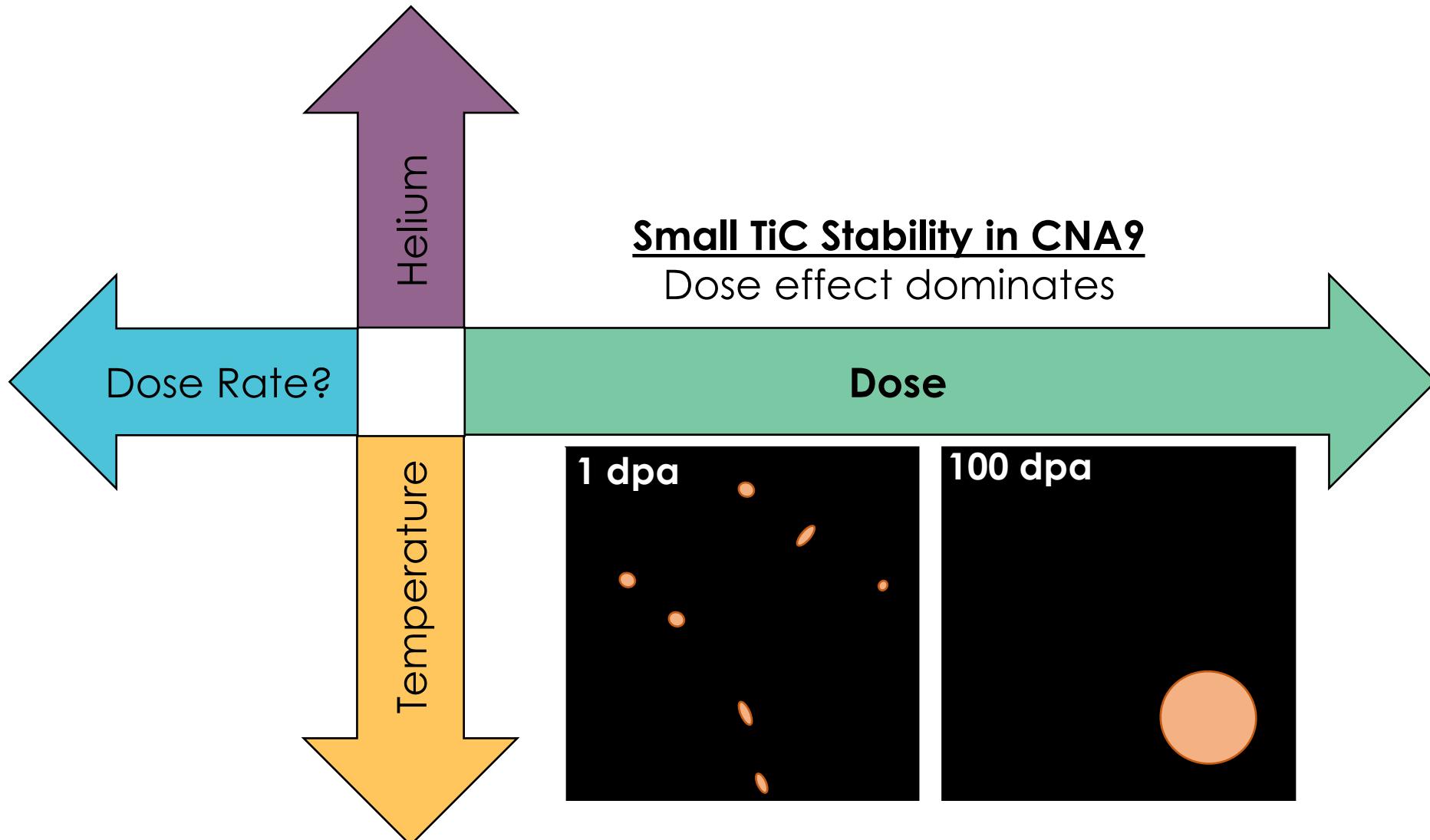
# HELIUM CO-INJECTION EFFECT

For a given temperature, dose effect dominates over helium effects





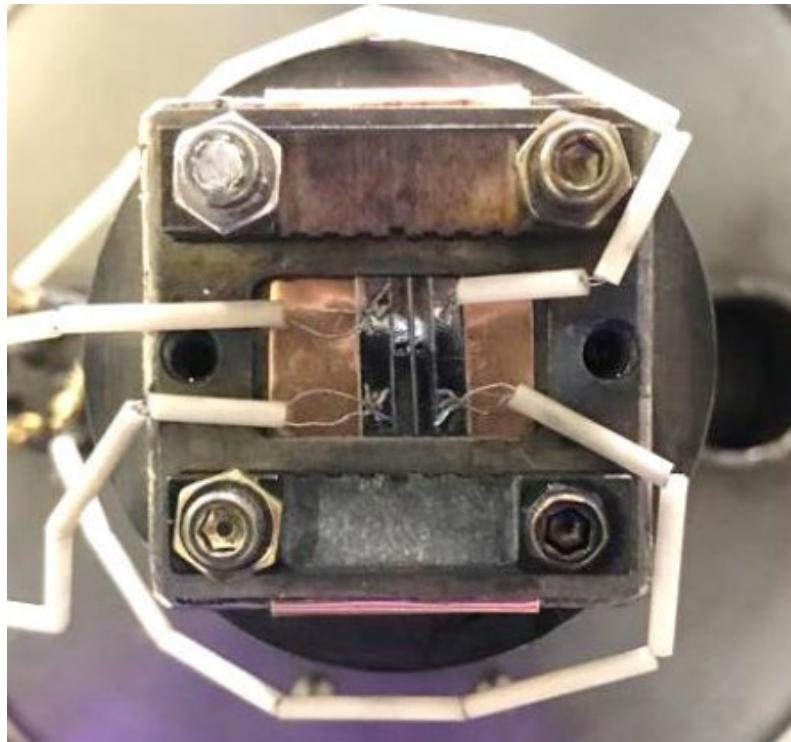
# Evolution of nanoprecipitates in CNA9



# Extra Slides

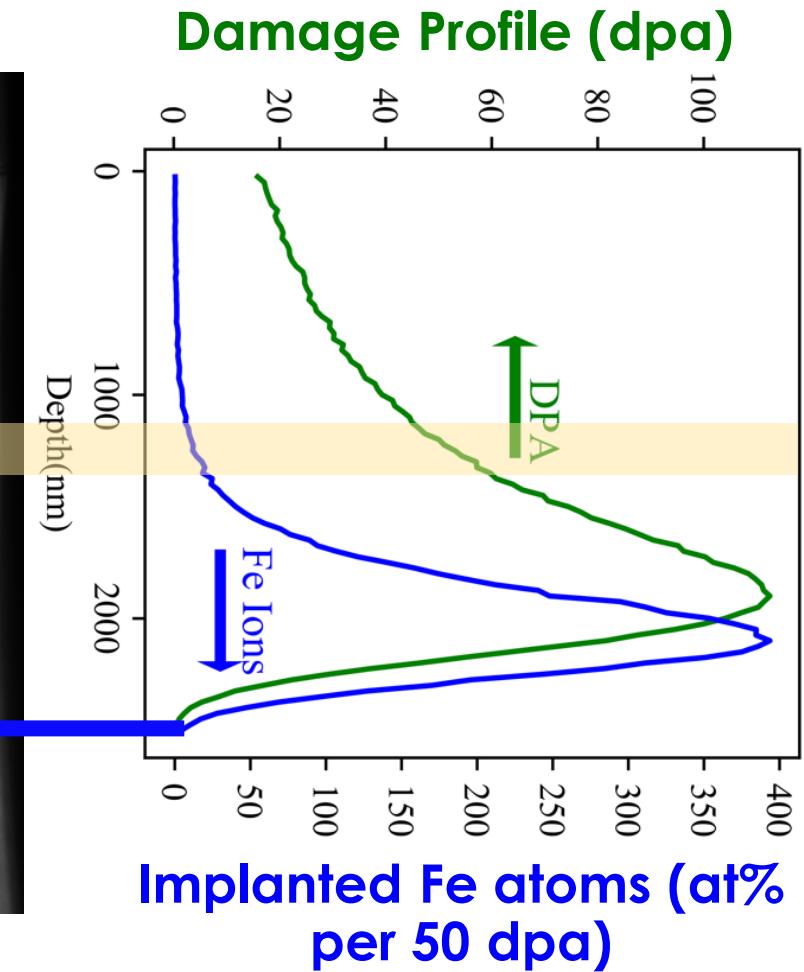
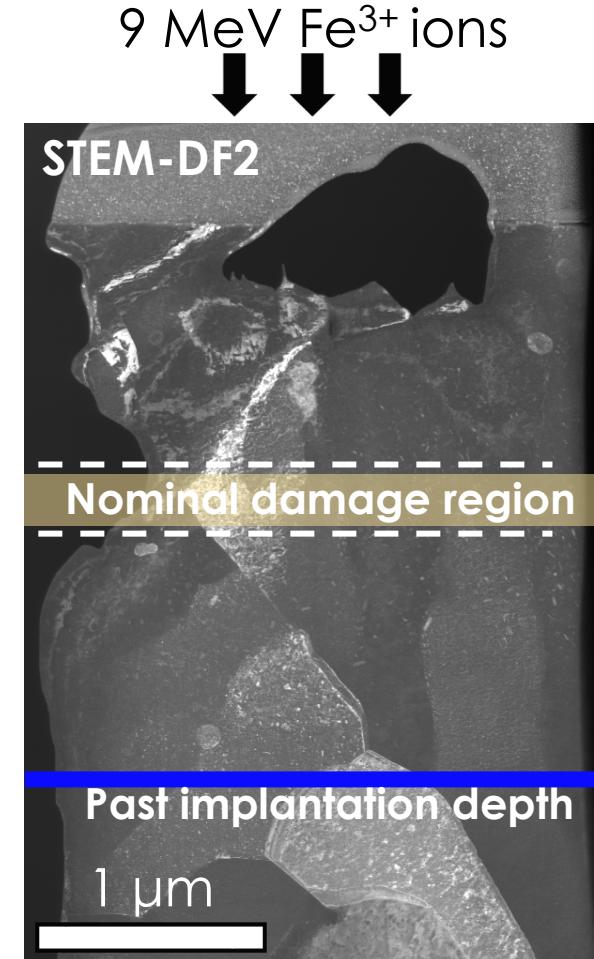
# 1 - Michigan Ion Beam Laboratory

Ex-situ irradiation with 9 MeV Fe<sup>3+</sup> ions



# 2 - Michigan Center for Materials Characterization

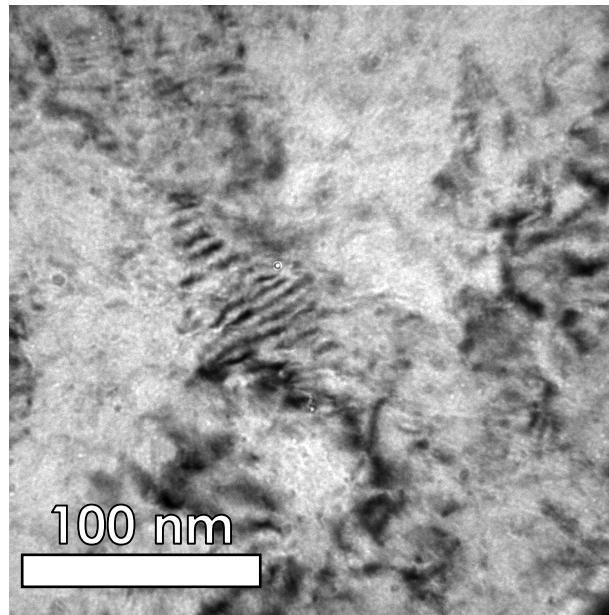
FIB, S/TEM, STEM-EDS



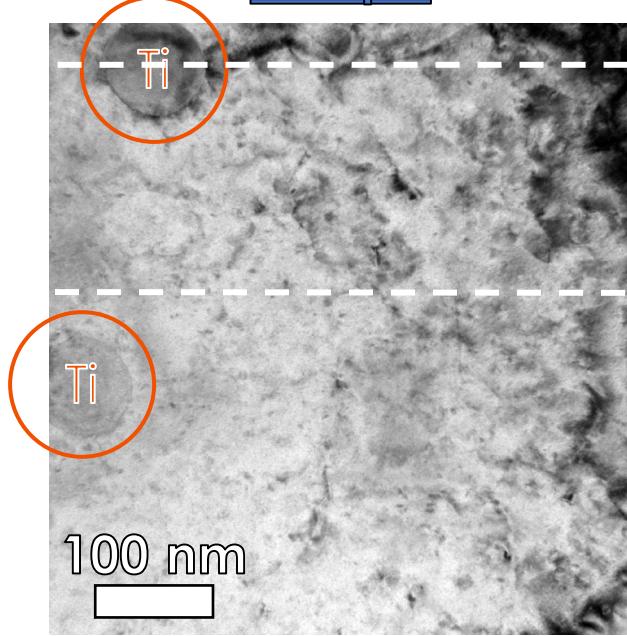


# HELIUM CO-INJECTION SERIES: 500°C, $7 \times 10^{-4}$ dpa/s,

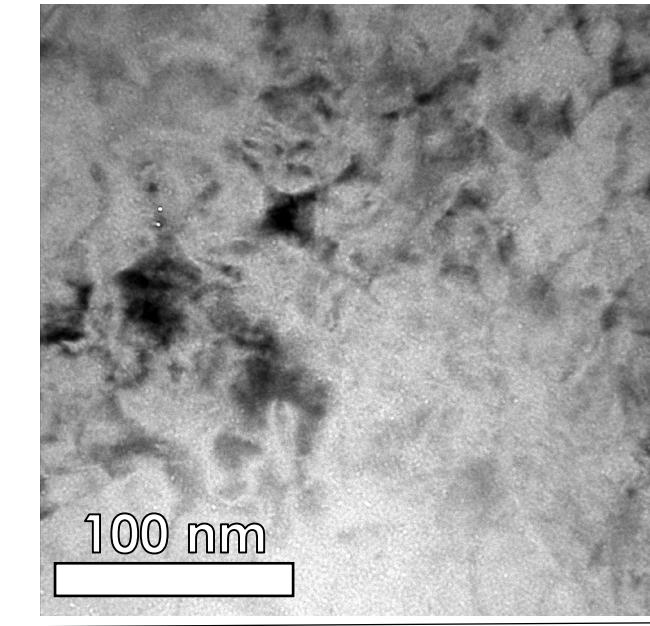
15 dpa



50 dpa



100 dpa



10 appm He/dpa

