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The role of Ti and TiC in Ti-stabilized austenitic steel under ion irradiation

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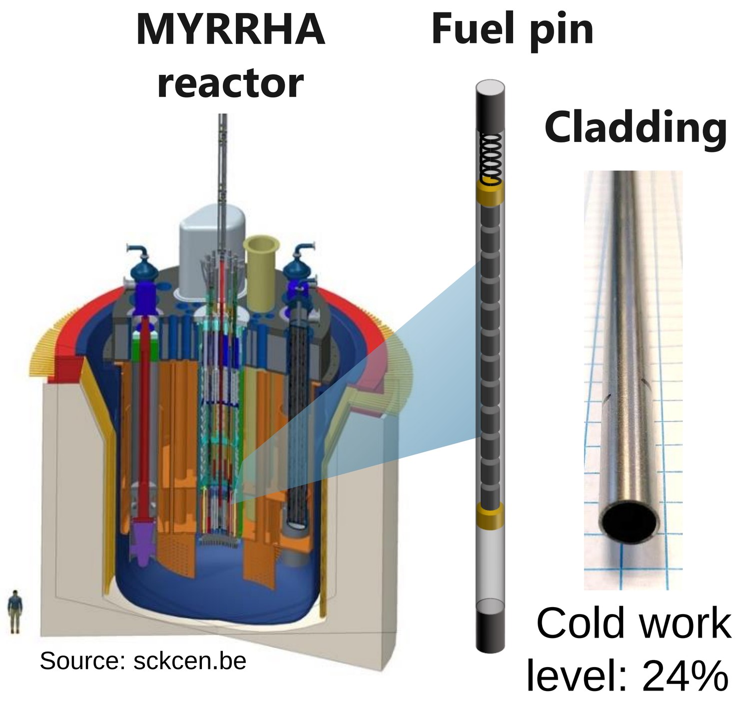
Introduction and objective

Ti-stabilized austenitic steels are prime candidate materials for fuel cladding in the first cores of future liquid metal cooled fast reactors, as they have been successfully applied for this purpose in the past [1]. Elevated temperatures and high fluxes of fast neutrons can cause rapid degradation to mechanical properties and volumetric swelling in austenitic steels [2]. Ti combines with C in the steel to form TiC nanoprecipitates, which are thought to act as point defect sinks and recombination centers [3], thereby delaying some of the adverse effects of radiation and increase the lifetime of the component. By combining advanced characterization techniques such as APT and TEM, this work sheds new light on the role of these precipitates with regard to radiation resistance.

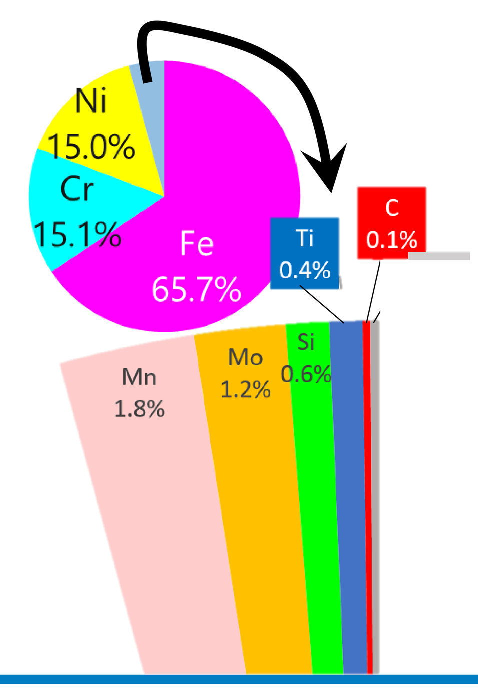
[1] J. Seran, et al., in: Eff. Radiat. Mater. 14th Int. Symp., ASTM publication, Andover, USA, 1990: pp. 739–752.
[2] F. Garner, J. Nucl. Mater. 122 (1984) 459–471.
[3] H. Bergmann et al., Entwicklung des Werkstoffs X10CrNiMoTiB 15 15 als Strukturmaterial für Brennelemente, FZK and Interatom/Siemens-KWU, 2003. https://tinyurl.com/y2ufw7ns.

Materials



As-received (NHT)

Composition



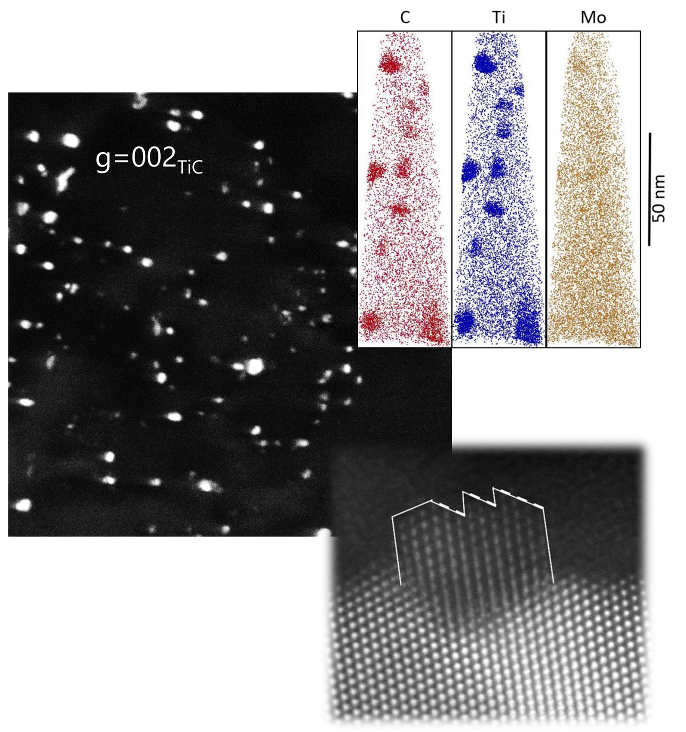
Structure

- Austenite (FCC) matrix
  - 10-15 µm grain size
  - 50-200 nm dislocation cells
  - Some grains heavily twinned
- Secondary phases (Primary precipitates)
  - Ti(N,C) of 1-10 µm
  - (Ti,Mo)C of 0.05-1 µm

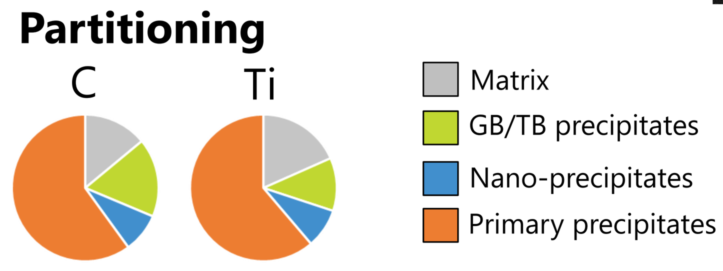
Heat treated (HT) 800 °C / 2 h

Precipitation

- Intragranular precipitation
  - TiC nanoprecipitates
    - N.D.: $(4 \pm 2) \times 10^{22}\ m^{-3}$
    - Avg. diameter: 3.6 - 4 nm
- Intergranular precipitation
  - coarse $M_{23}C_6$
  - coarse TiC

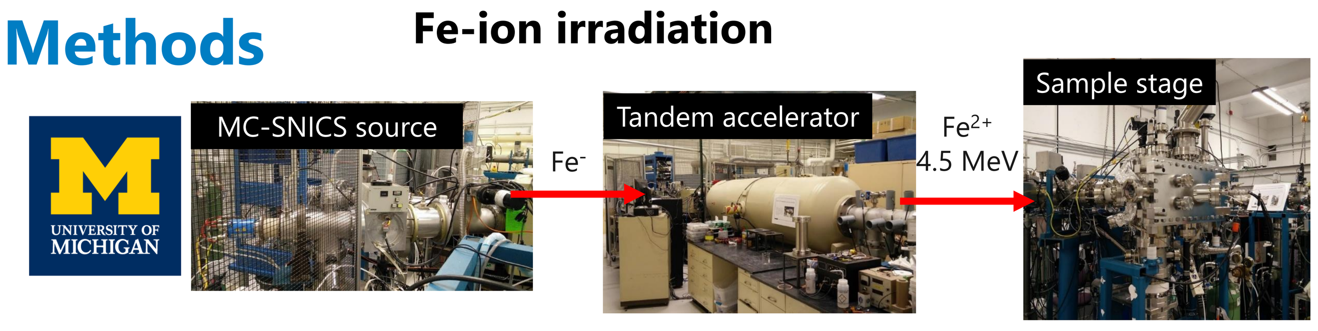


Partitioning

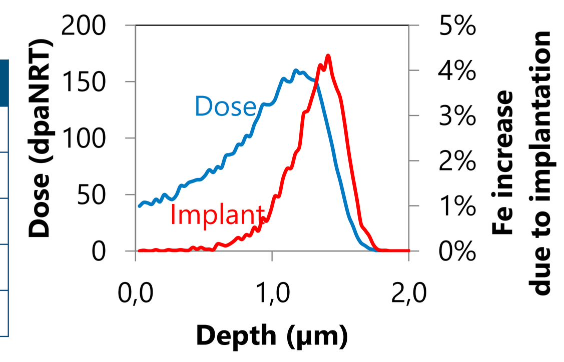


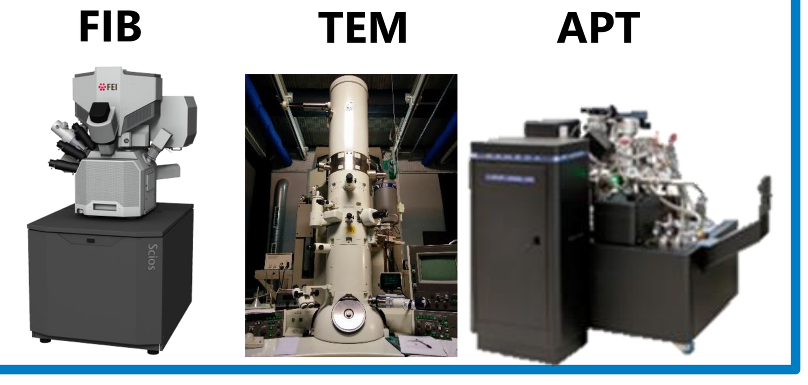
Methods

Fe-ion irradiation



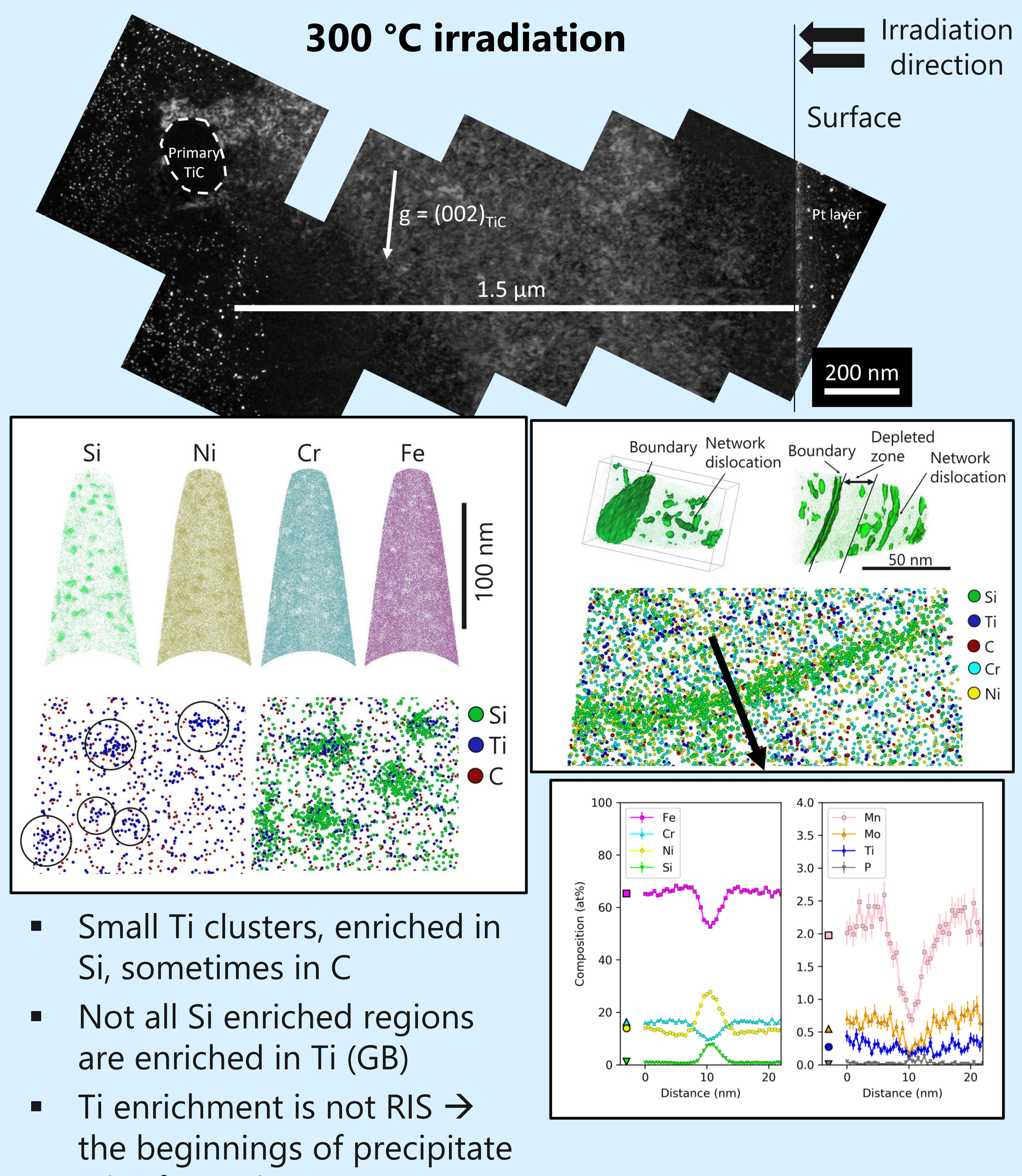
Parameter	Value
Ion	Fe^{2+}
Energy	4.5 MeV
(Surf.) Dose	40 dpa
(Surf.) Dose rate	$\sim 2 \times 10^{-4}$ dpa/s
Temperatures	300, 450, 600 °C





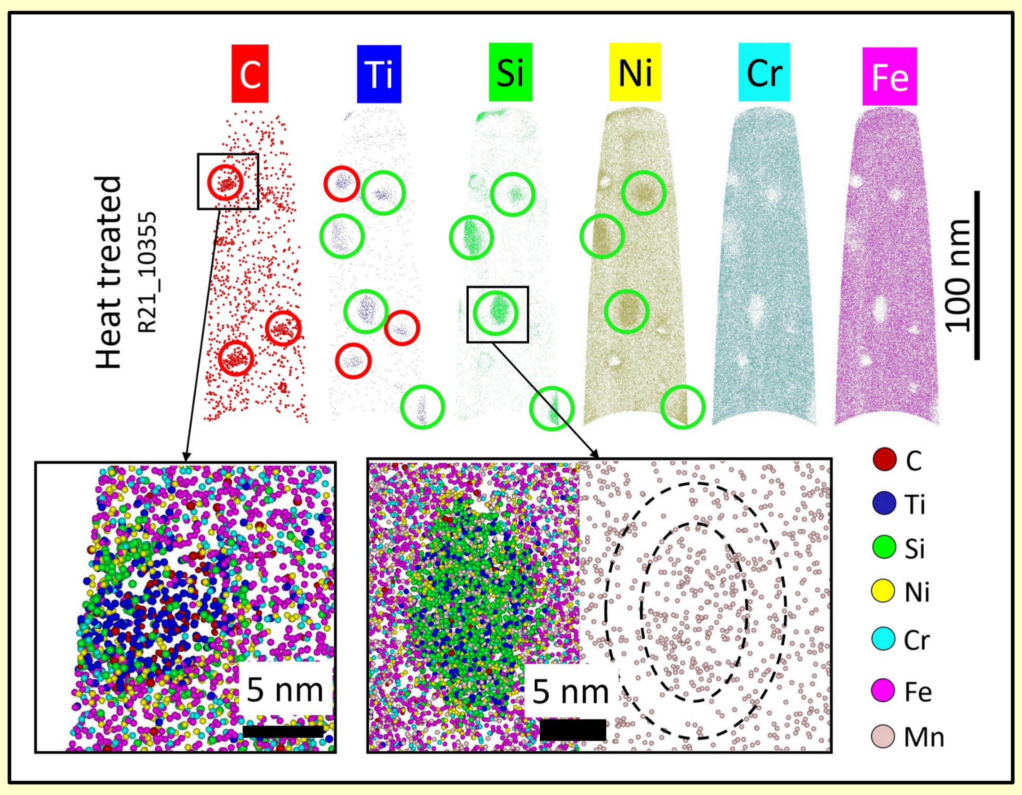
Results

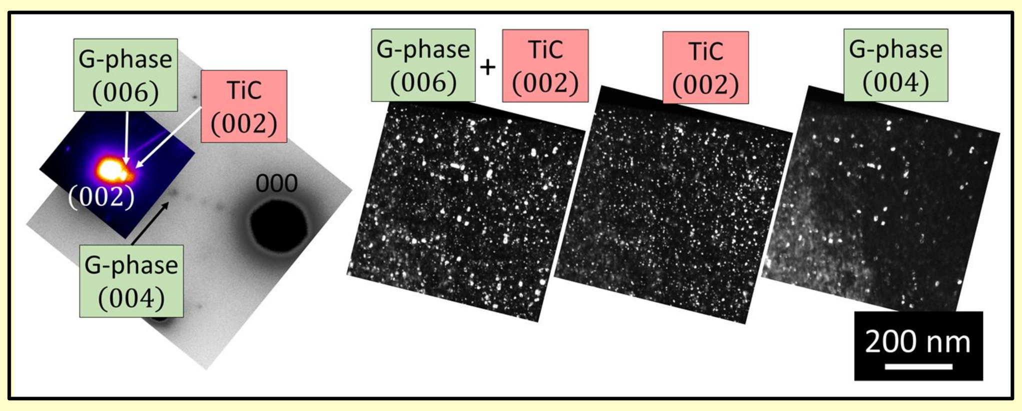
300 °C irradiation



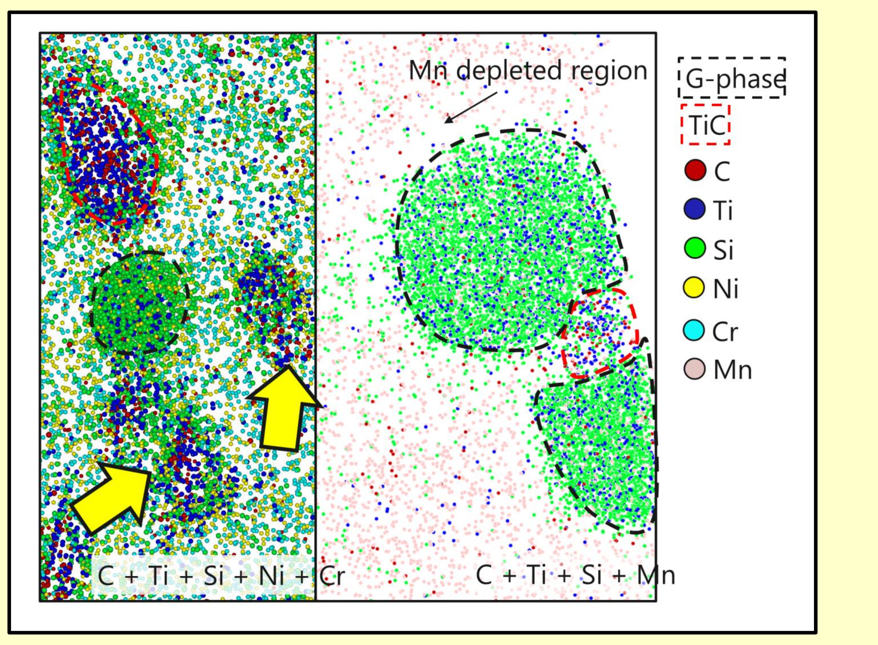
- Small Ti clusters, enriched in Si, sometimes in C
- Not all Si enriched regions are enriched in Ti (GB)
- Ti enrichment is not RIS → the beginnings of precipitate (TiC) formation?

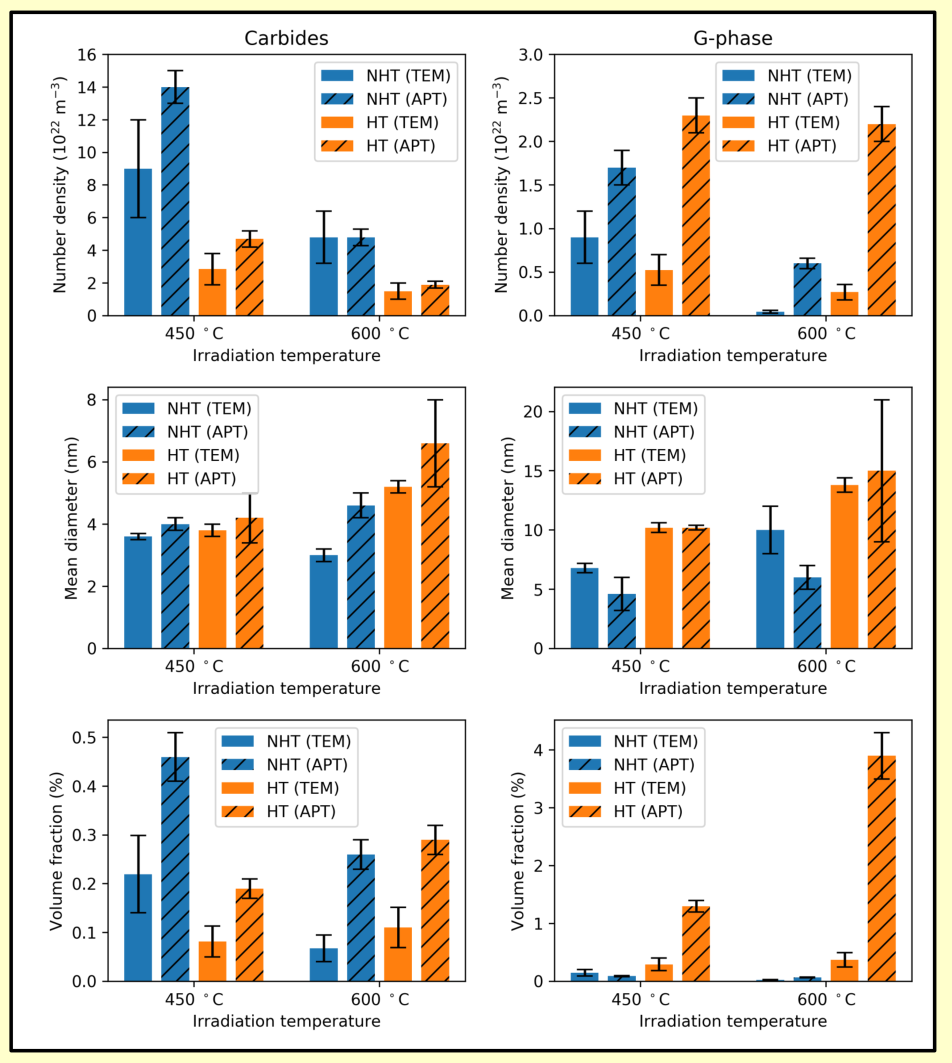
450 and 600 °C irradiation





- TiC found in c.w. (NHT) and aged (HT) conditions after irradiation
  - N.D. particles NHT > N.D. particles HT
- "Shells" of Si and Ni enrichment around TiC
- Some G-phase (Ni-Si-Ti-Mn phase) particles appear to grow on TiC with complex O.R.
  - V.F. G-phase NHT < V.F. G-phase HT





Conclusion

▪At low irradiation temperatures, nanoprecipitates are unstable. Microstructure evolves to similar steady state. Small clusters of Ti observed, possibly TiC nuclei.
▪At elevated irradiation temperatures, TiC particles act as important sinks and/or recombination centers for point defects. More TiC means less G-phase and is thus likely favorable. G-phase is associated with other degradation phenomena such as swelling. Heat treatment is deleterious to final number density of TiC.
▪May be promising for MYRRHA: a higher solution annealing temperature to increase Ti in solution and increased cold work level. These will only help at high temperature

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