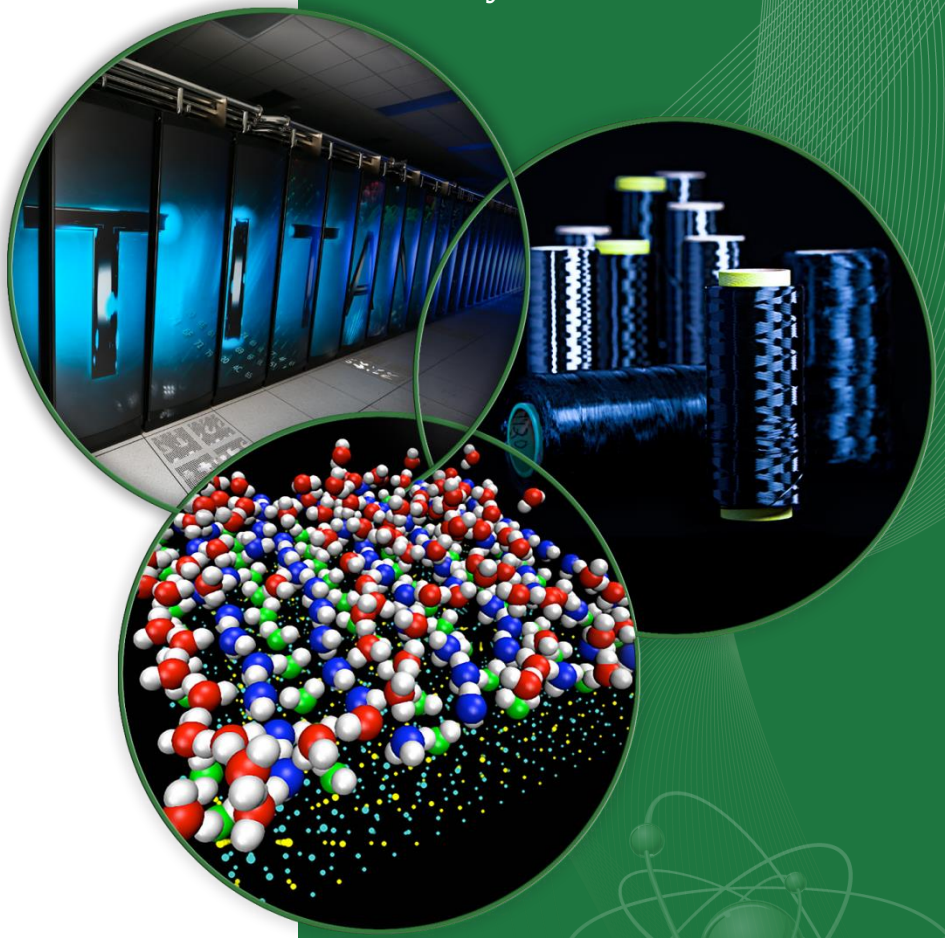
The Fusion Materials Workshop
July 26, 2016
University of Tennessee, Knoxville

SiC composites & Ceramics: Irradiation Effects at High Doses



Presented by

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ORNL is managed by UT-Battelle
for the US Department of Energy

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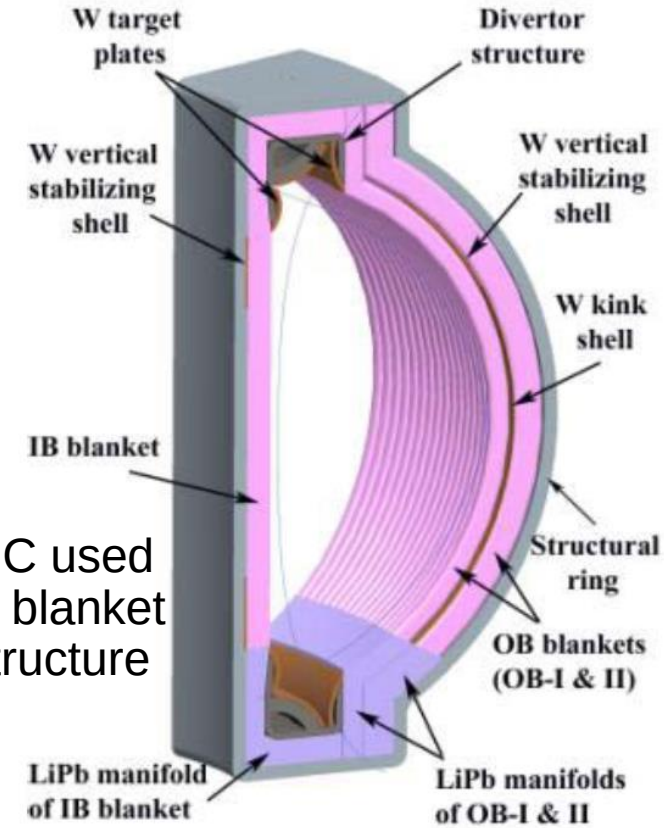
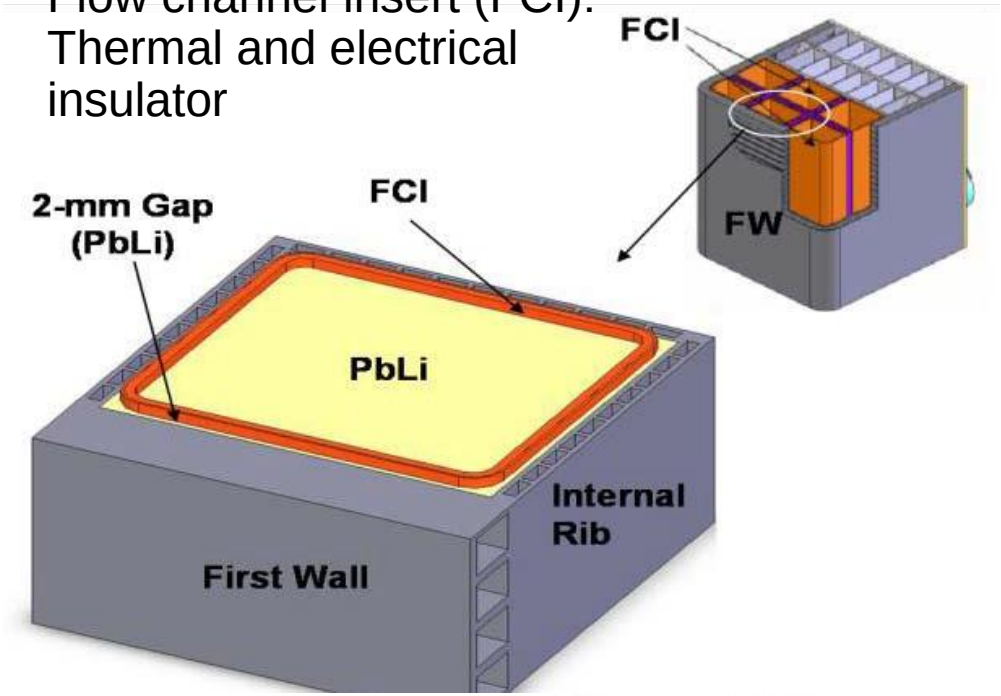
Applications of SiC for fusion and the expected irradiation conditions



SiC used as blanket structure

Flow channel insert (FCI): Thermal and electrical insulator



Temperature: 700-1000°C

Temperature: up to ~800°C

Wang, X. R., et al. *Fusion Science and Technology* 64.3 (2013): 455-459.

Sharafat, Shahram, et al. *Fusion Science and Technology* 56.2 (2009): 883-891.

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Irradiation data accumulation on early nuclear grade SiC composite

Properties	Low dose	High dose	Transmutation effect	Note
Mechanical properties	◎	○	×	Moderate degradation at high irradiation temperature and significant degradation at low temperature
Thermal properties	◎	○	×	No obvious change from ~1dpa
Swelling	◎	○	△	No obvious change from ~1dpa
Irradiation creep	×	×	×	• CVD SiC and SiC fibers investigated • Limited creep strain expected
Electrical properties	○	×	×	• Possible limiting factor for FCI application • Significant contribution from transmutation elements

Data available ◎ ○ △ × Data limited

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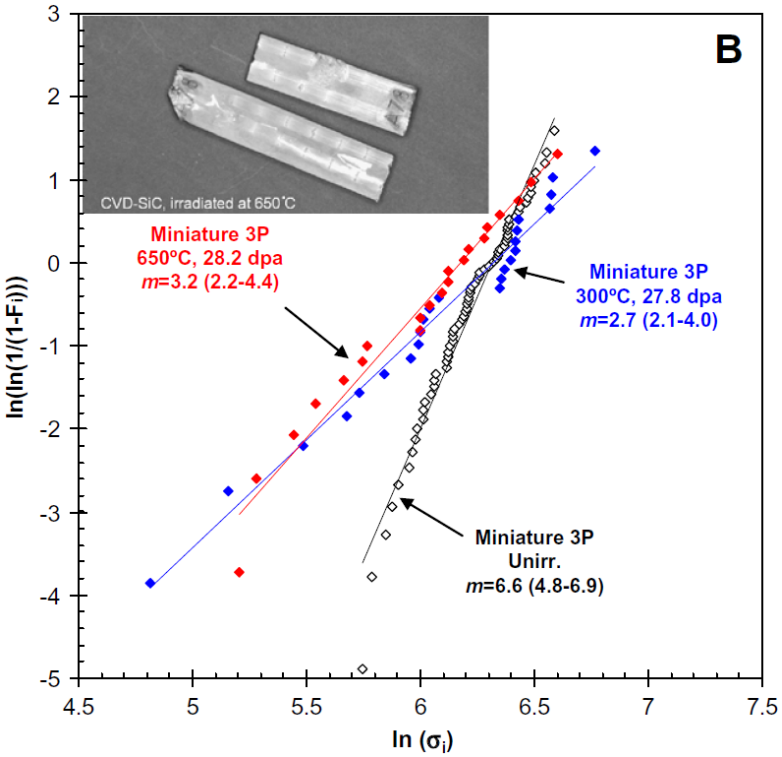
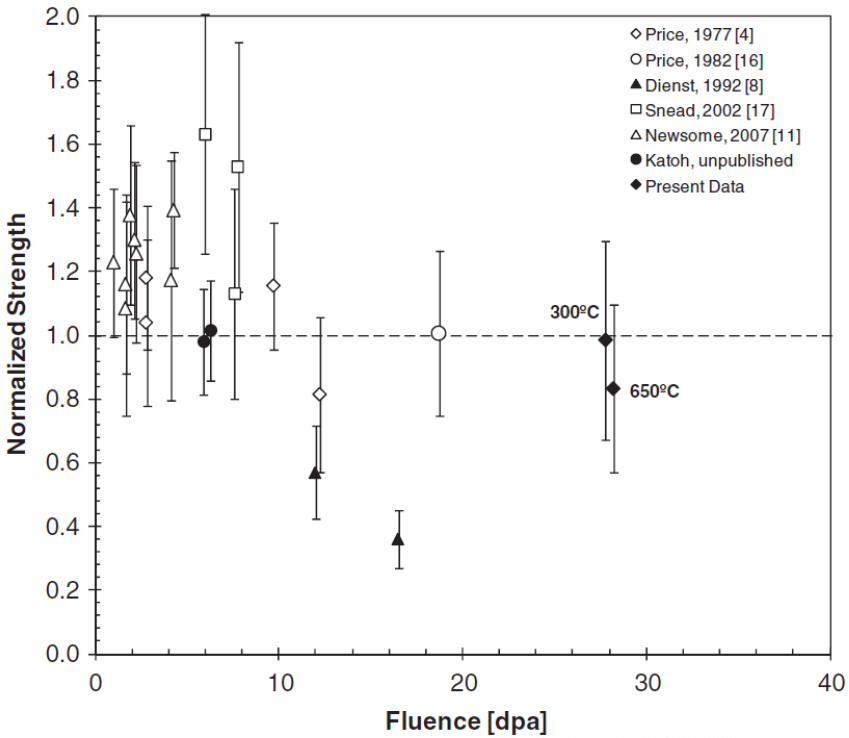
Strength of high-purity SiC ceramics at high doses





- No obvious strength degradation of “high-purity” monolithic, chemical vapor deposited (CVD) SiC up to ~30dpa.
- No indication of mechanical degradation of CVD SiC up to ~70dpa.

Katoh, Yutai, et al. *Journal of Nuclear Materials* 417.1 (2011): 400-405.
Katoh, Yutai, et al. *Journal of Nuclear Materials* 462 (2015): 450-457.

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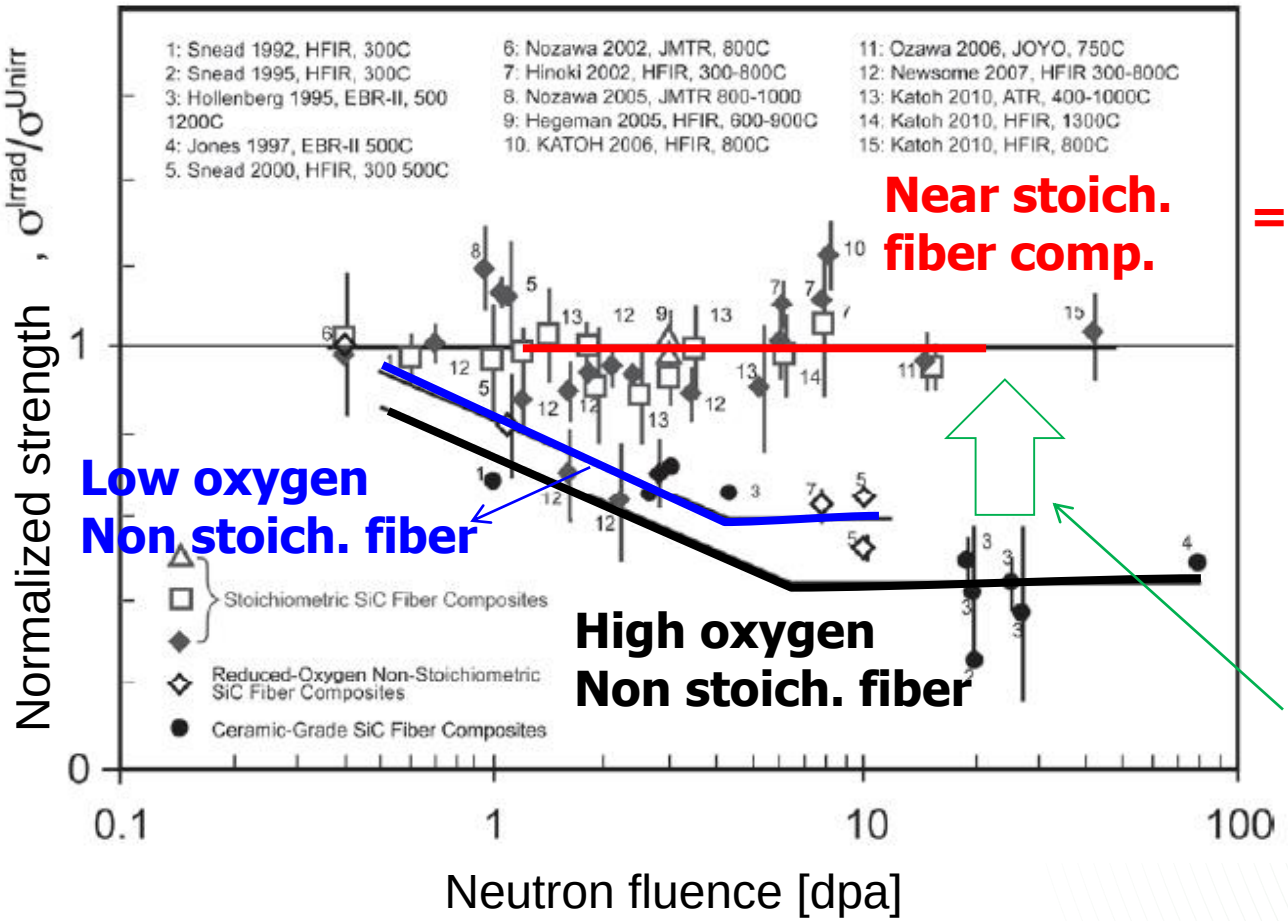
Strength of irradiated SiC composites at high doses



=> **Nuclear grade SiC comp.**

Acquisition of radiation resistance by fiber improvement

Snead, L. L., et al. *Journal of Nuclear Materials* 417.1 (2011): 330-339.

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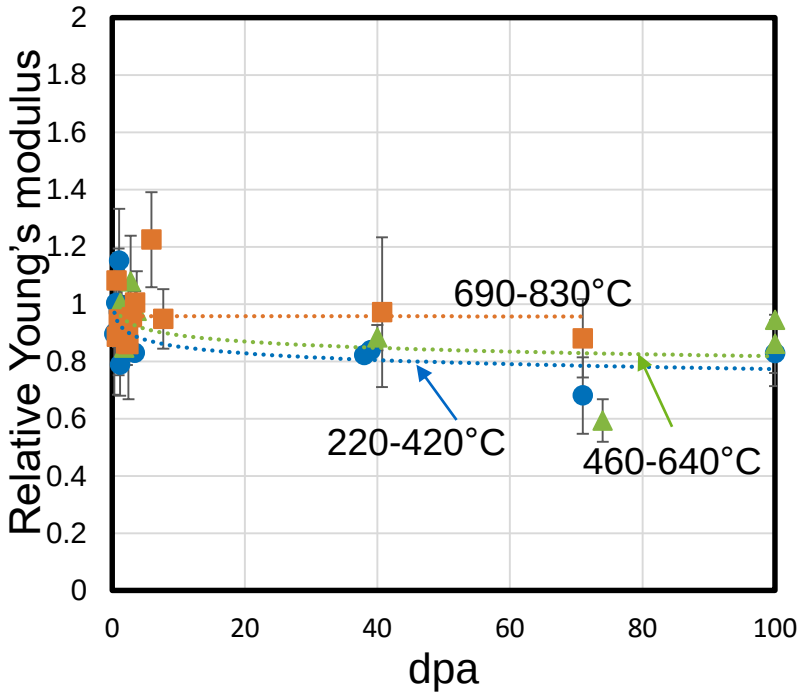
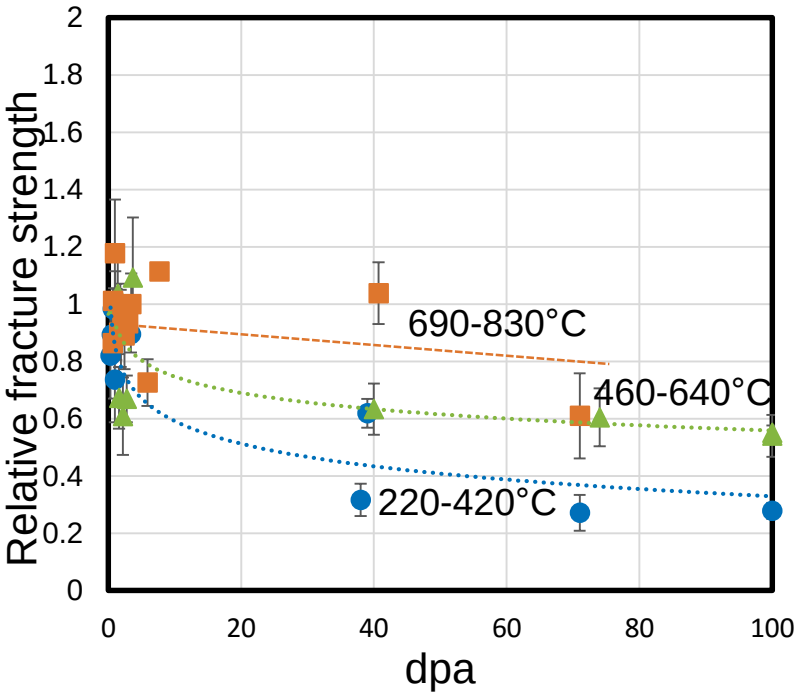
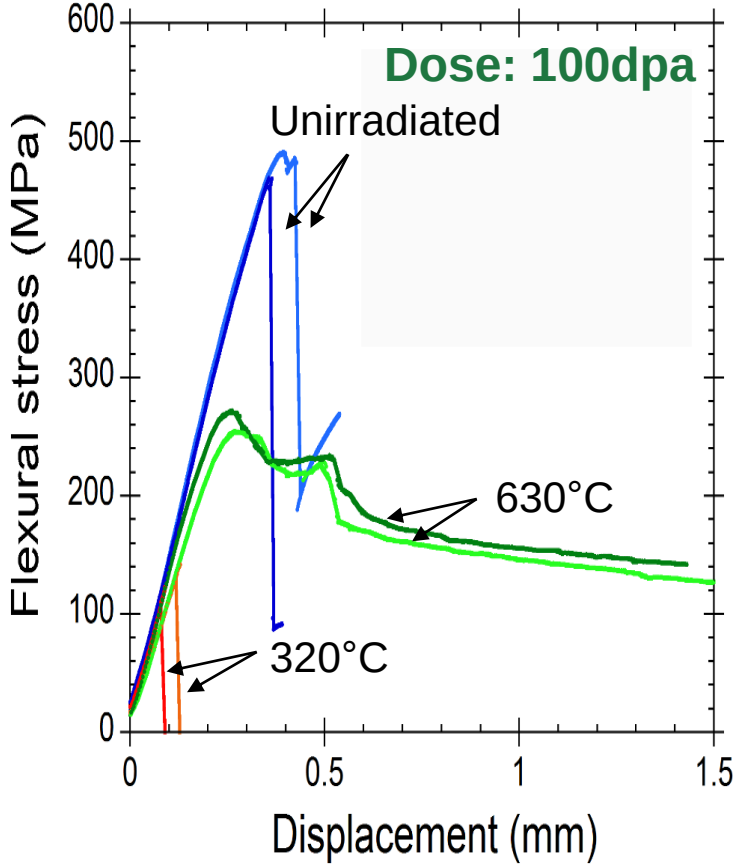
Recent milestone of neutron irradiation to 100dpa was achieved in DOE-JAEA collaboration.

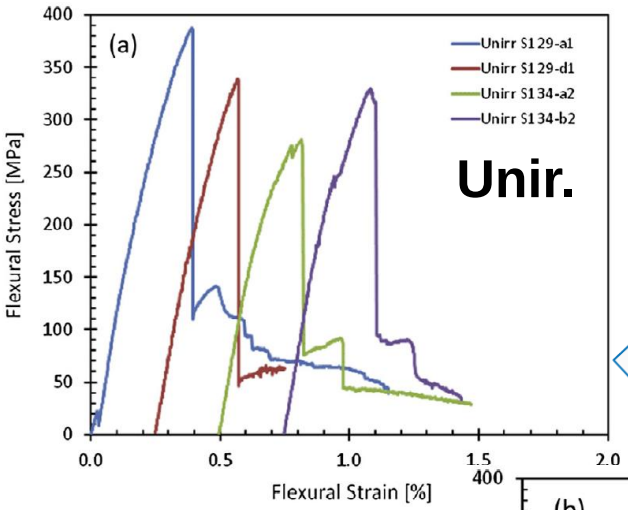
Material: 1st generation nuclear grade SiC composites
Chemical vapor infiltration SiC matrix / Hi-Nicalon Type-S SiC fiber / Pyrolytic C-SiC multi-layer interphase

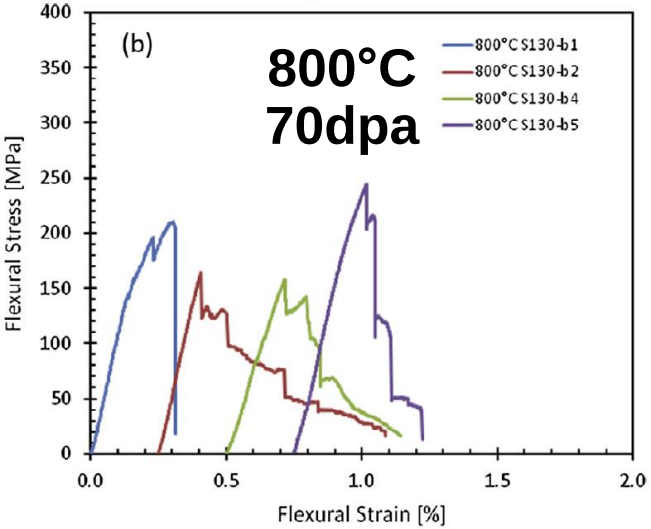




Fracture behavior following irradiation to 100dpa





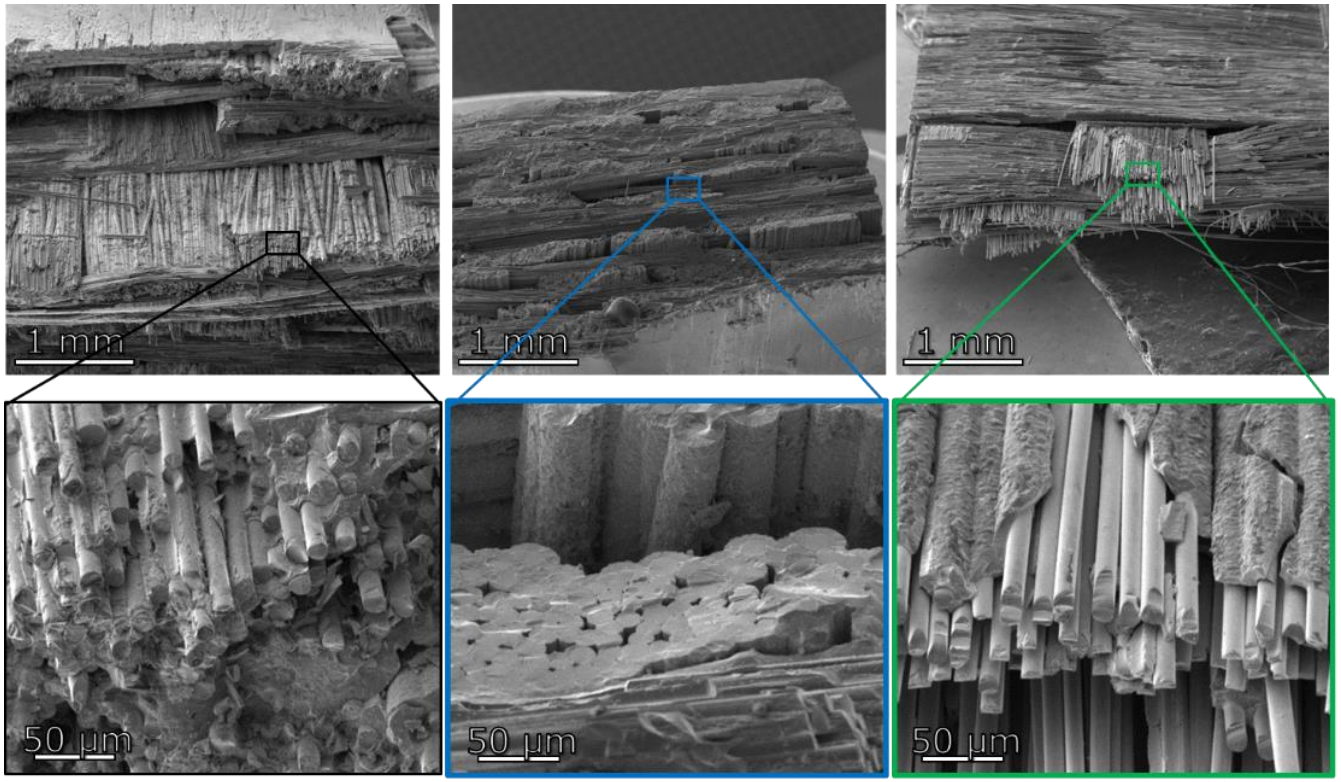


- No indication of degradation of CVI SiC matrix based on modulus, swelling and thermal properties
- Strength degradation => Fiber damage
- Brittle fracture => Interphase degradation

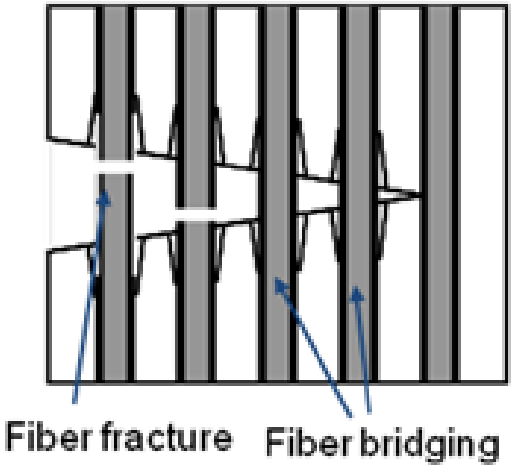
Katoh, Yutai, et al. *Journal of Nuclear Materials* 462 (2015): 450-457.

Fracture behavior following irradiation to 100dpa

Unirradiated | 320°C/100dpa | 630°C/100dpa



Fiber Reinforcement Toughening Mechanisms



Typical for composite, fiber pull-out

No fiber pull-out, brittle fracture

Long fiber pull-out

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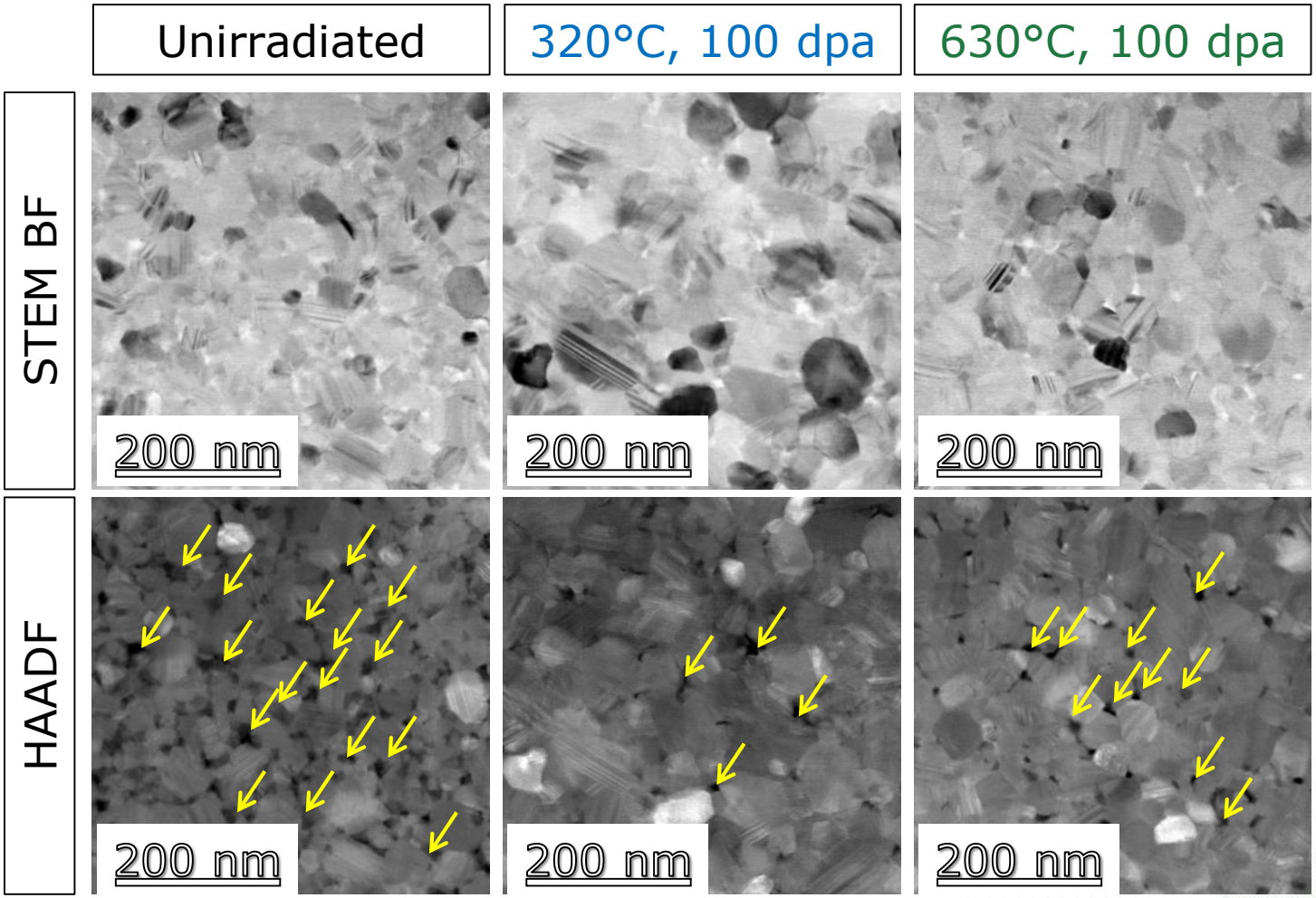
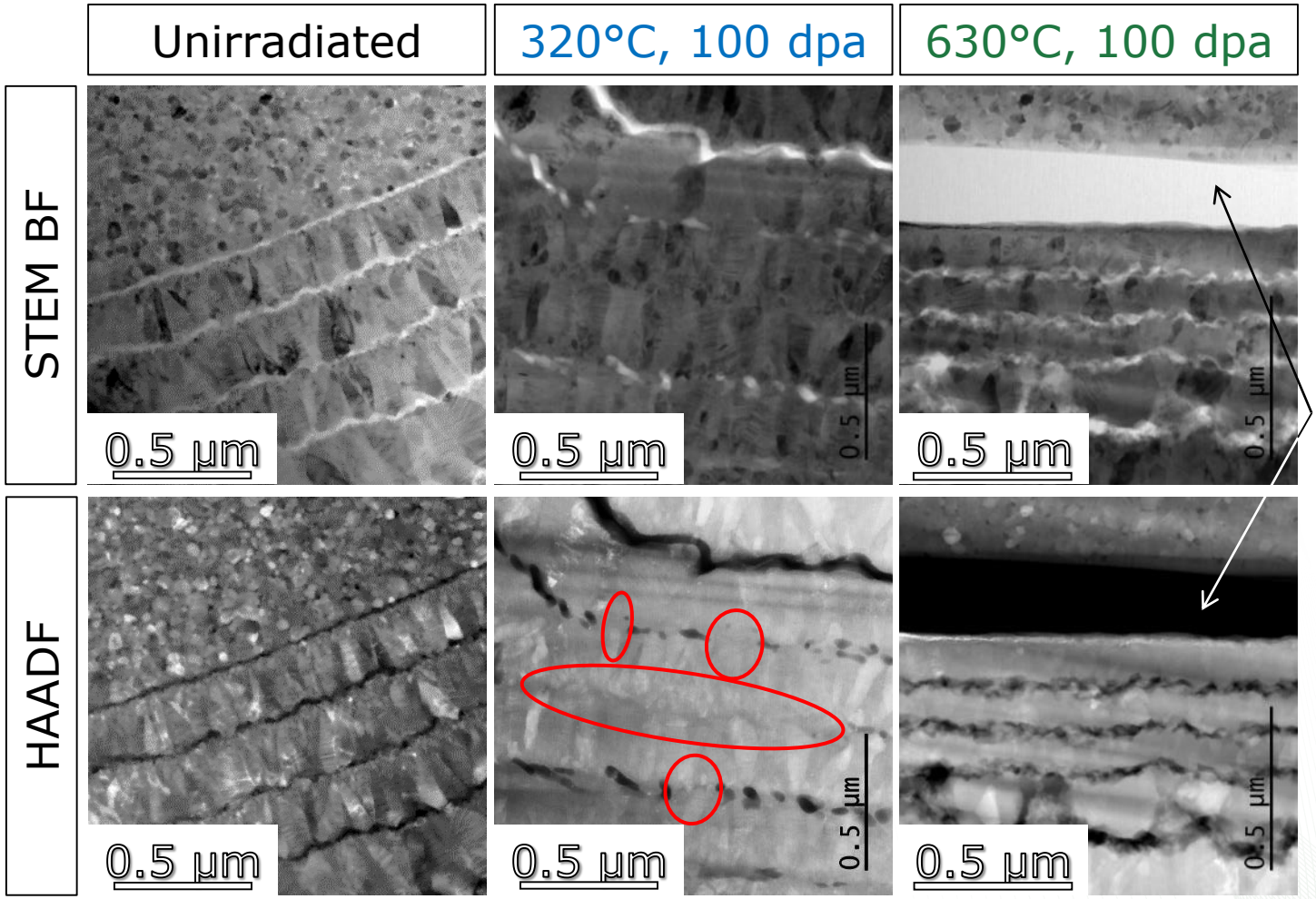
Microstructural instability of Hi Nicalon Type S SiC fiber



- Carbon packets reduced in all condition possibly by cascade mixing.
- The disappearing ratio is larger at 320°C.

Indication of interphase degradation



Detachment during FIB processing

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Options of constituents of SiC composite

SiC Matrix

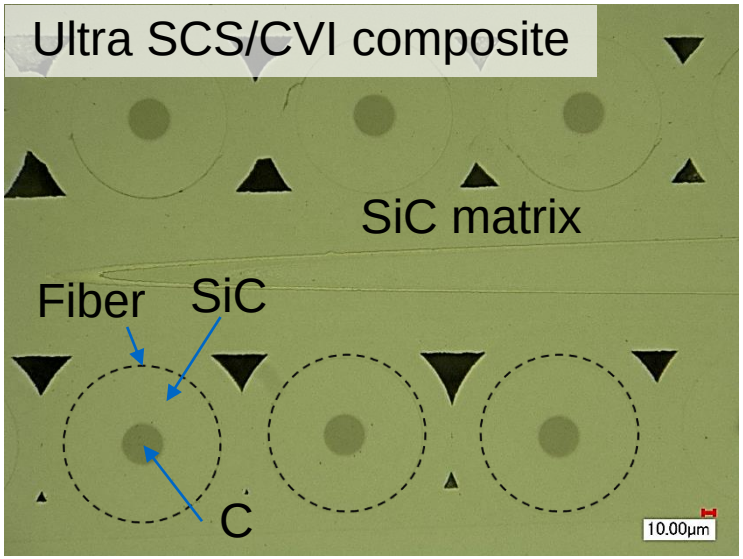
- High-purity CVI SiC

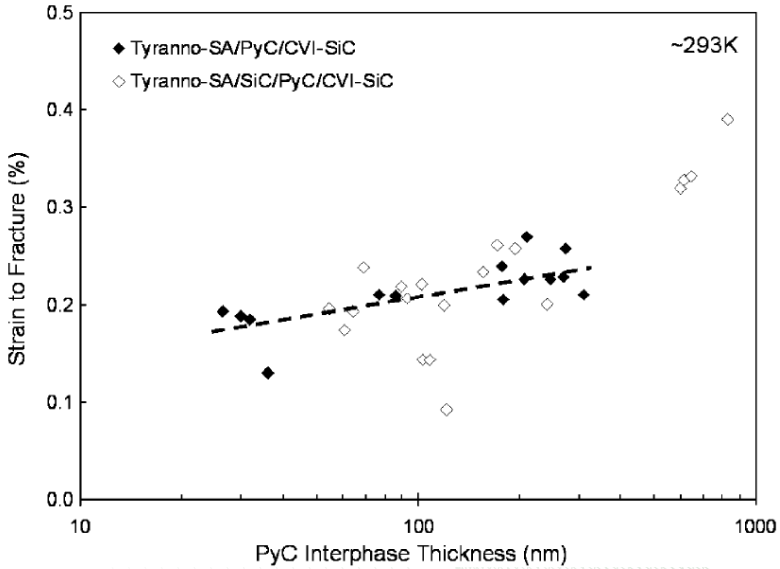
SiC Fiber

- Hi Nicalon Type S (used 1st generation nuclear grade composite)
- Tyranno SA (larger grains with carbon secondary phase)
- Ultra SCS (C core + CVD SiC)
- Laser chemical vapor deposited fiber by Free Form Fibers Co. (expected high purity CVD SiC)

Interphase

- Pyrolytic carbon with different thickness
- Pyrolytic carbon/SiC multi layer

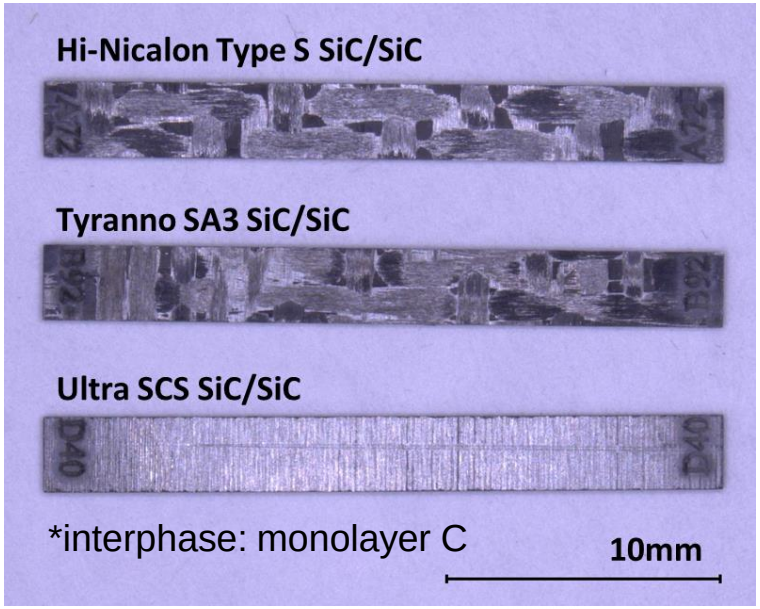




Katoh, Yutai et al. *Journal of the American Ceramic Society* 88.11 (2005): 3088-3095.

Ongoing high dose irradiations (1): newer nuclear grade SiC composites

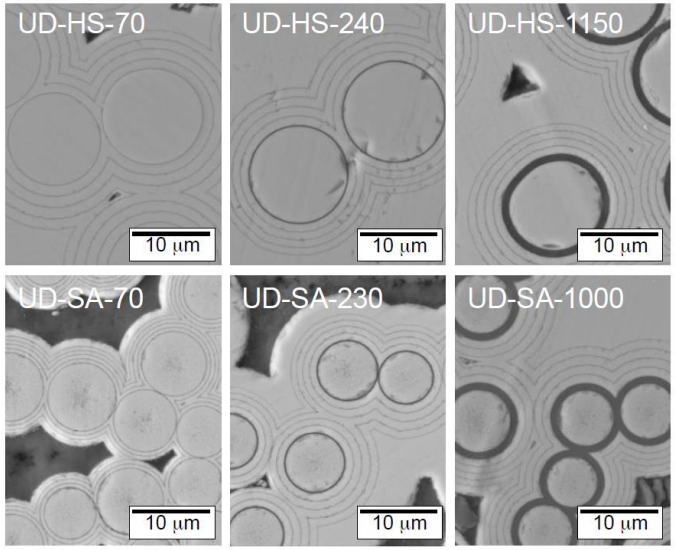
Target Temperature [C]	DPA	Program	Status
300	2	Fission (FCRD)	LAMDA
	10		LAMDA
	30		In-reactor
	100		In-reactor
	200		In-reactor
600	10	Fusion (DOE-JAEA collaboration)	LAMDA
	30		In-reactor
	100		In-reactor
	200		In-reactor
1000	10		LAMDA
	30		In-reactor
	100		In-reactor



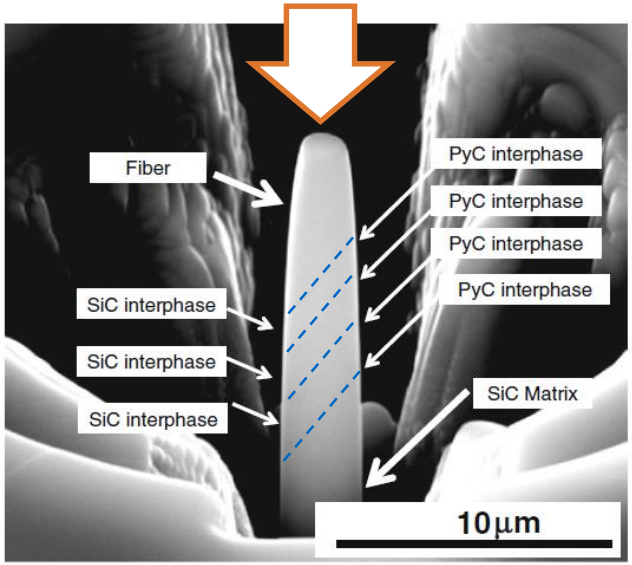
PIE: Dimensional stability, modulus, flexural strength, microstructure

Ongoing high dose irradiations (2): optimization of interphase

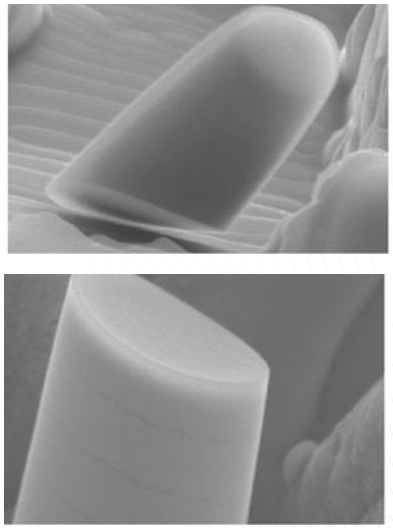
- Materials
  - CVI SiC/SiC
    - Hi Nicalon Type S and Tyranno SA3 fibers
    - Multilayer and monolayer interphases



- Irradiation: ~950°C/>100dpa
- PIE: Evaluation of the interfacial properties (micropillar compression)



Compression test



Shih, Chunghao, et al. *Journal of Materials Science* 48.15 (2013): 5219-5224.

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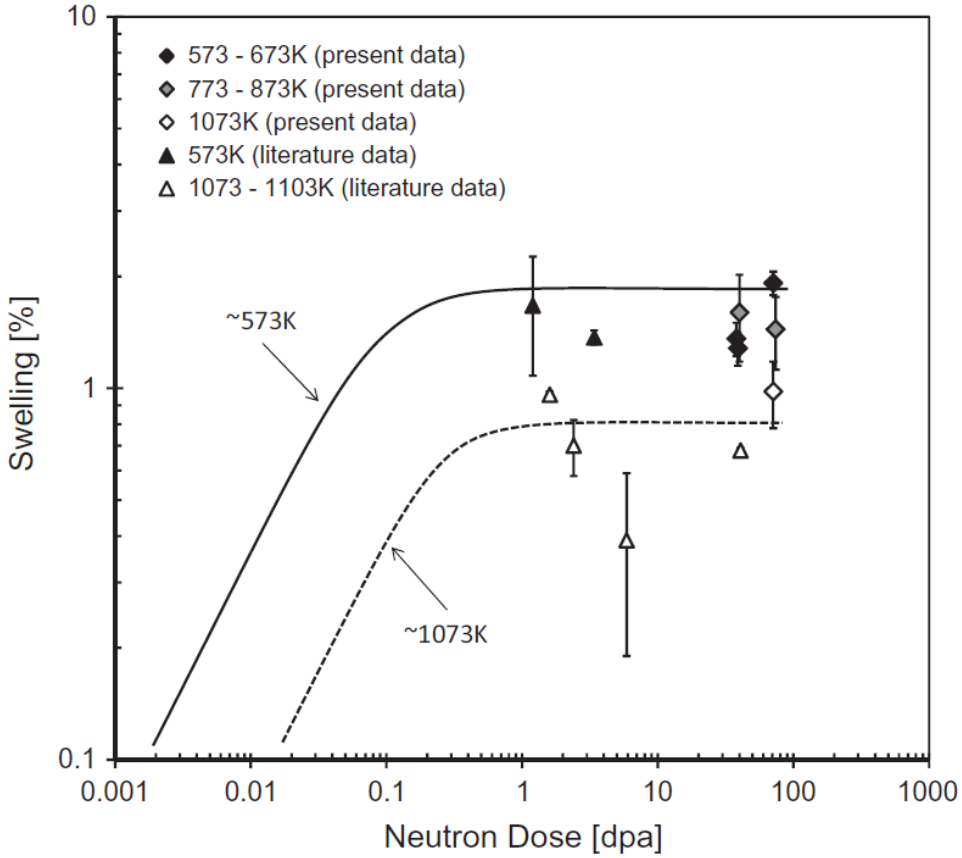
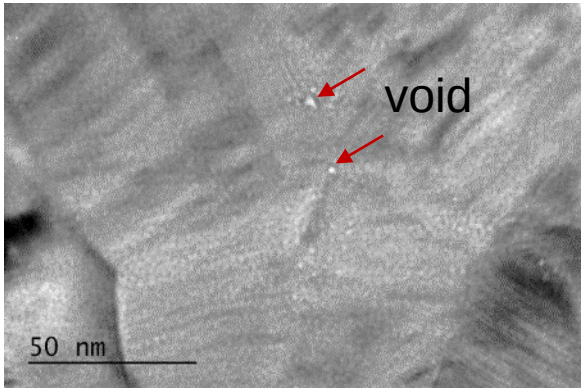
Saturation of swelling and stable microstructure of high-purity SiC

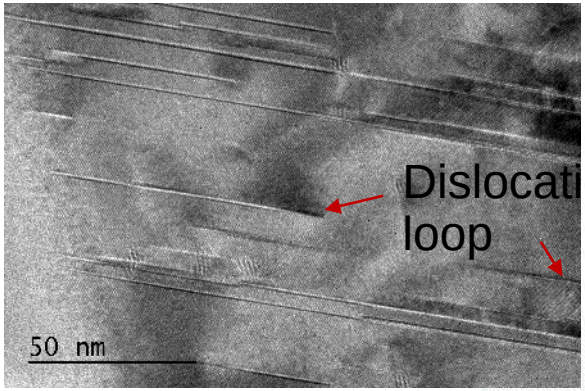
Hi Nicalon Type S fiber, CVI SiC matrix composites



CVI SiC matrix, 630C/100dpa



CVD SiC, 630C/100dpa



Katoh, Yutai, et al. *Journal of Nuclear Materials* 462 (2015): 450-457.

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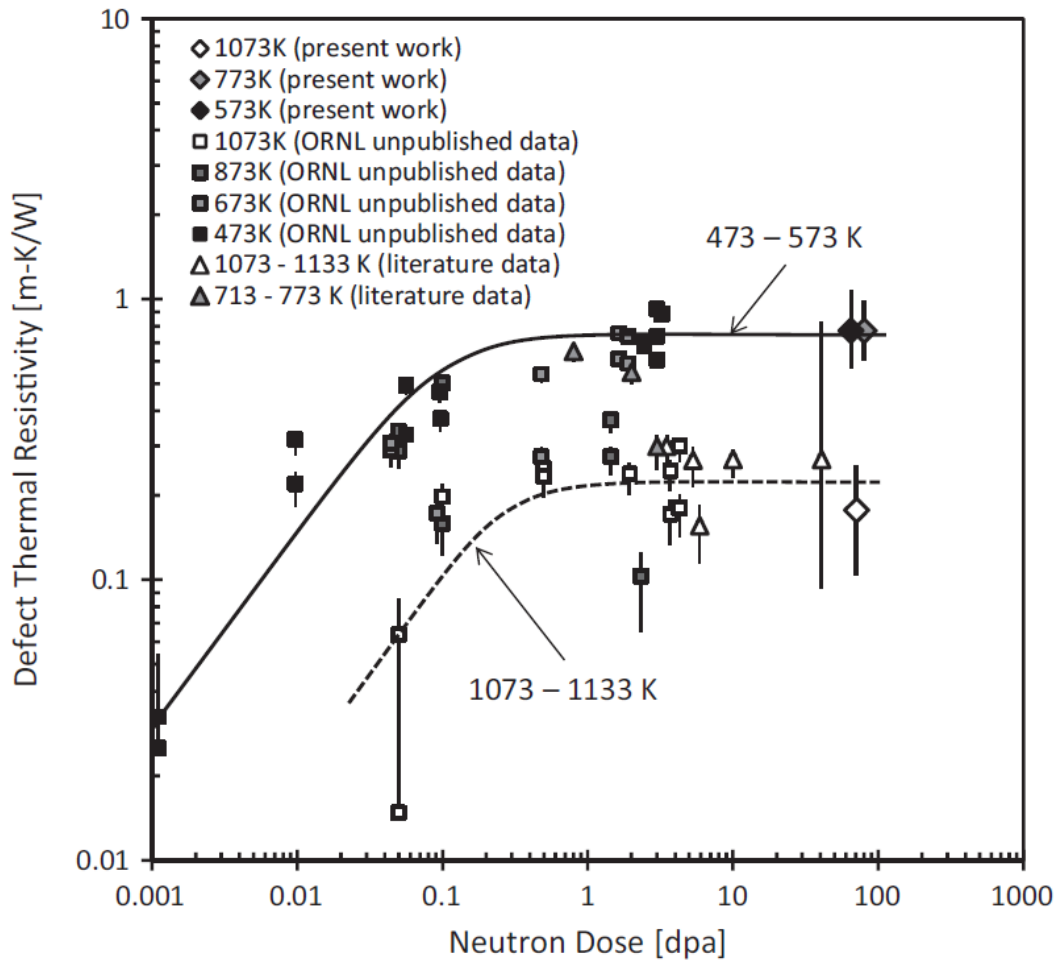
Saturation of thermal property of high dose irradiated Hi-Nocalon Type S fiber, CVI SiC matrix composite



$$\frac{1}{K_{DT}} = \frac{1}{K_{IR}} - \frac{1}{K_0}$$

Defect Thermal Resistivity

Irradiated Thermal Conductivity

Unirradiated Thermal Conductivity

Katoh, Yutai, et al. *Journal of Nuclear Materials* 462 (2015): 450-457.

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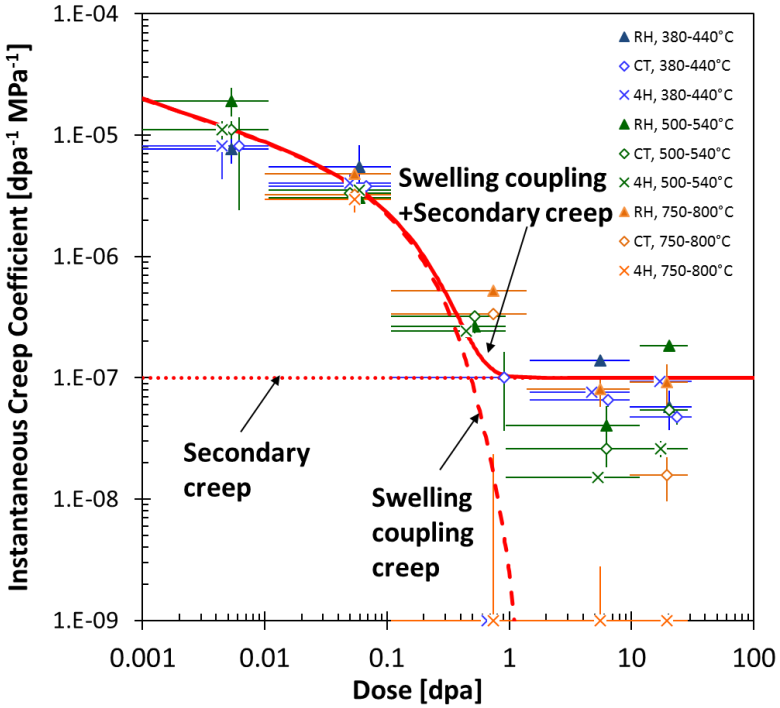
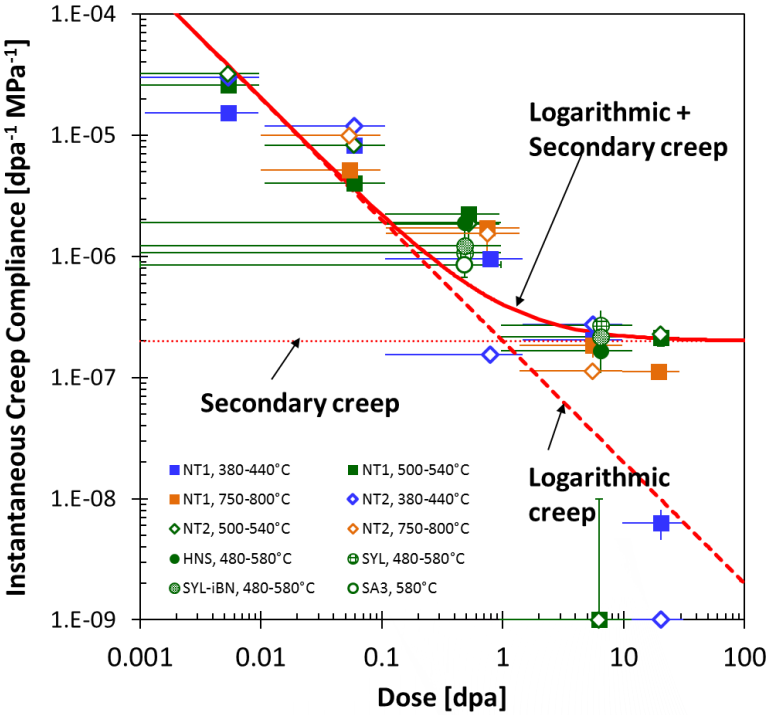
High-dose irradiation creep of SiC materials



High-purity CVD SiC, 380-800°C



SiC fibers and sintered SiC, 380-800°C

- Secondary irradiation creep operated from ~1dpa.
- Radiation creep is expected to be not an critical issue since creep strain was limited (much smaller than lattice strain associated with swelling).

Koyanagi, Takaaki, et al. *Journal of Nuclear Materials* 478 (2016): 97-111.

Conclusions and future directions

- Irradiation resistance of early nuclear grade Hi Nicalon Type S, CVI SiC composite was investigated up to 100dpa. The mechanical degradation was relatively moderate at higher radiation temperature and significant at low temperature.

- Fiber and interfacial damage was severe following high dose, low temperature irradiations. Optimization of fiber and interphase materials is ongoing under DOE-JAEA (QST) collaboration.

- Irradiation effects on dimensional stability and thermal properties appeared to be not a critical issue.

- Simultaneous effects of irradiation damage and formation of transmutation elements are needed to be understood.

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