PAUL SCHERRER INSTITUT
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Wir schaffen Wissen – heute für morgen

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Suggestion of a novel failure tolerant fuel element & SiC related experiments at PSI

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  - Mechanical testing of neutron irradiated SiC/C & SiC/SiC

New fuel concept for for LWR – Annular pin

Suggestion of hollow pellet design in order to limit the temperature

Yong Sik YANG, KAERI, Journal of NUCLEAR SCIENCE and TECHNOLOGY, Vol. 46, No. 8, p. 836–845 (2009)

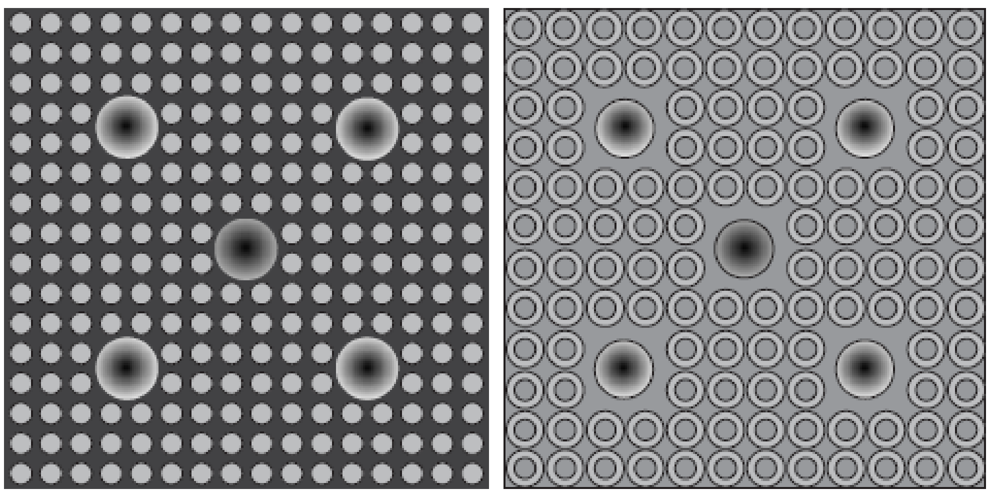
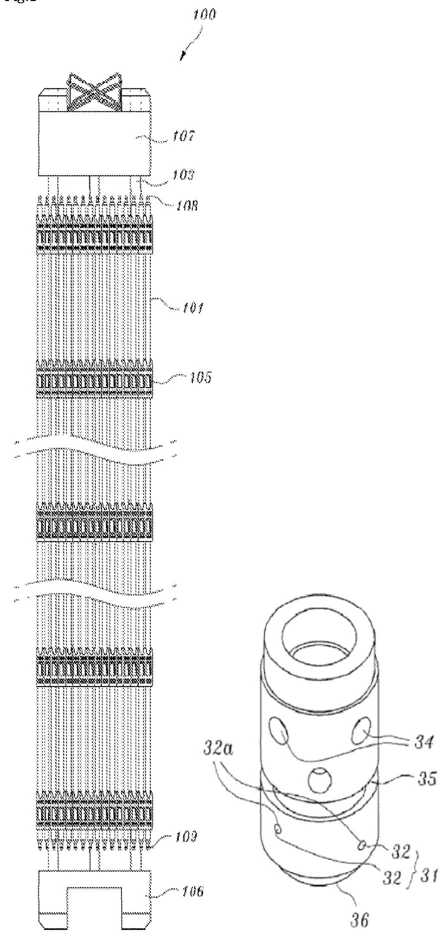


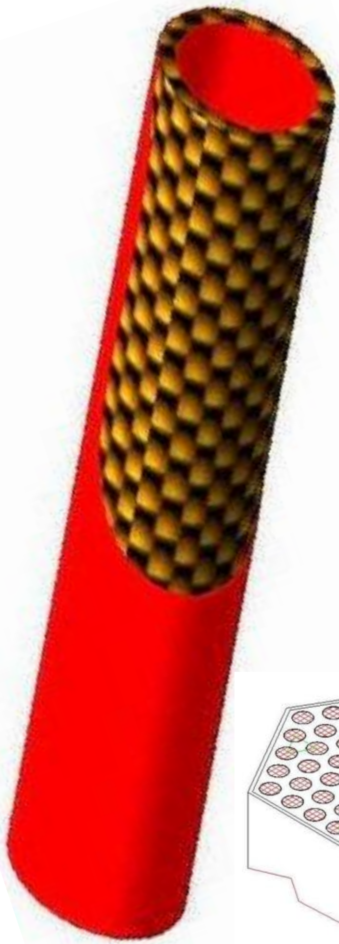
Fig.1



US Patent 2008/0013667 A1

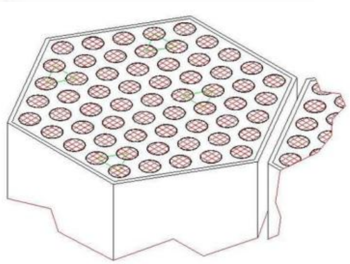
- Effective concept to lower the temperature (+)
- Very sophisticated fuel production necessary (-)

GFR Fuel - Pin design: SP option

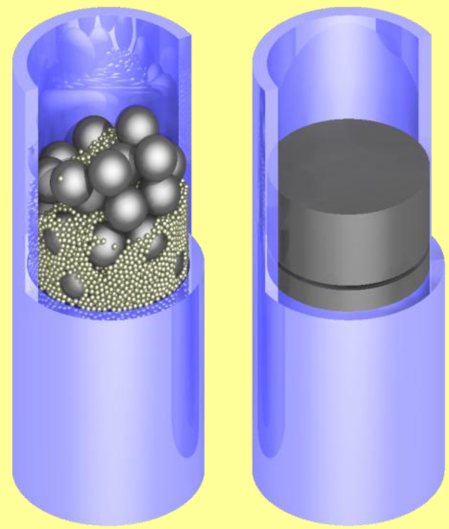


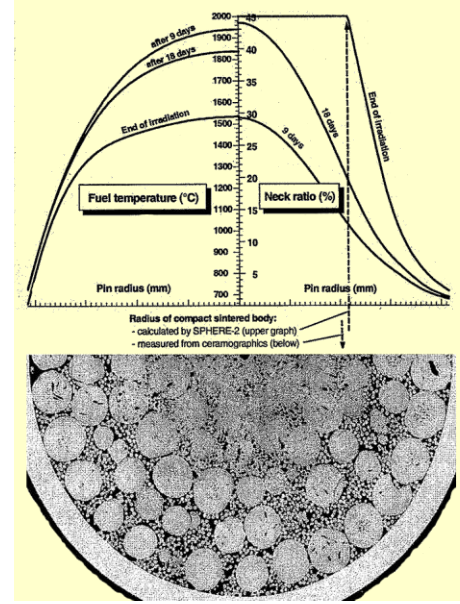
Cladding:
- Ceramic (SiC/SiC) with inner liner
- Thickness: 1mm
- Diameters: 6.15mm/8.15mm

Pellet:
- Carbide
- Diameter: 5.92



Suggestion of SP filling:
→ Favorable swelling behavior (softer)

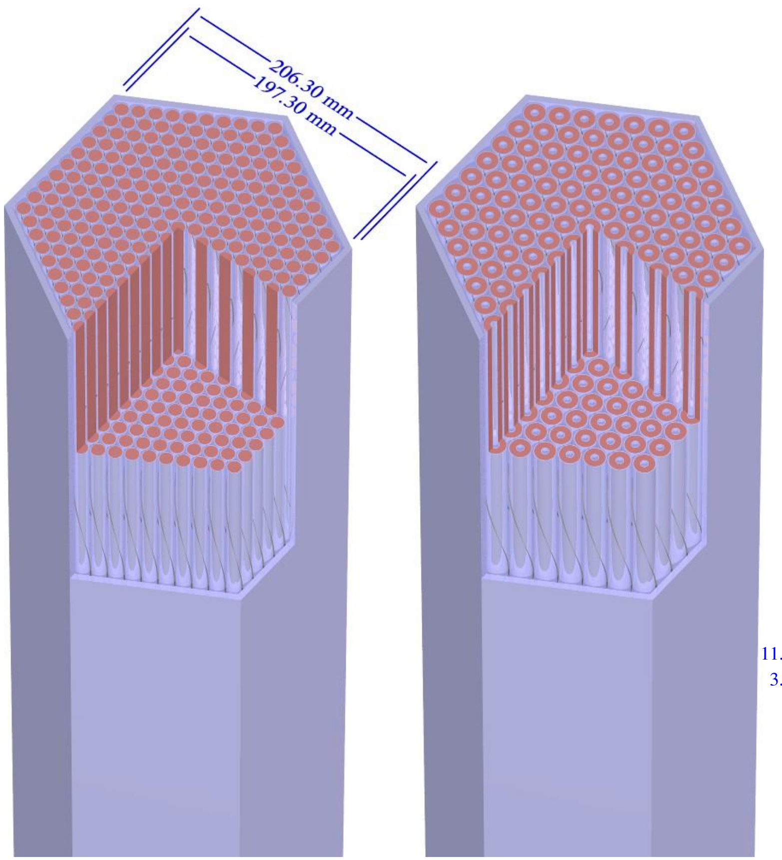


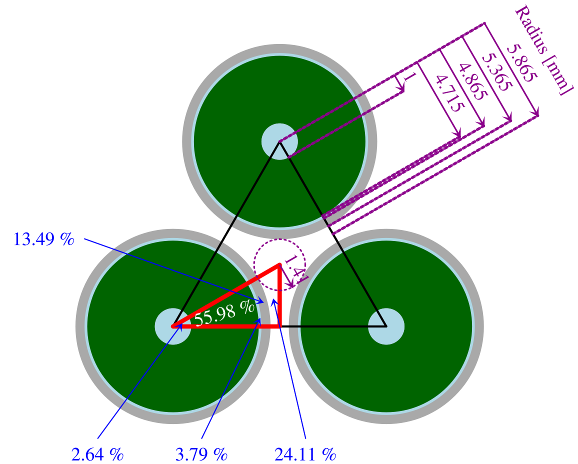


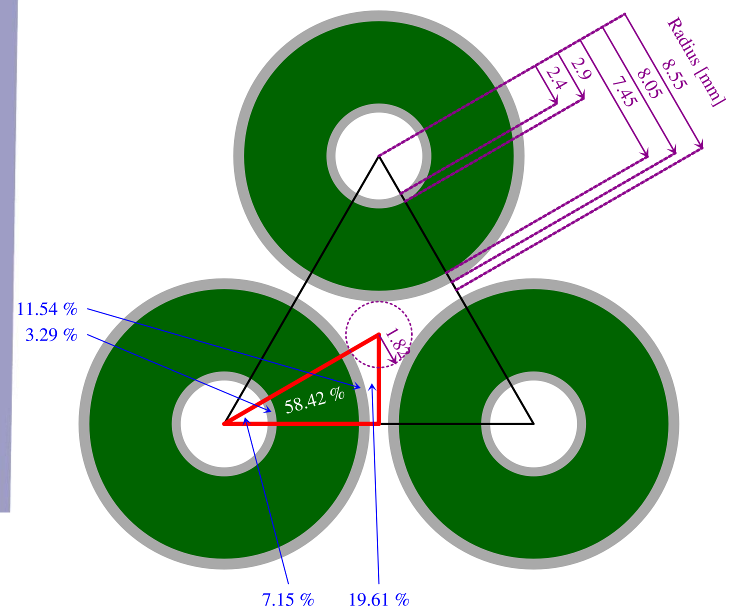
AC3- Experiment Carbide fuel in fast reactor → low FCMI (soft)

Bart, G., Botta, F. B., Hoth, C. W., Ledergerber, G., Mason, R. E., and Stratton, R. W. (2008). AC-3-irradiation test of sphere-pac and pellet (U,Pu)c fuel in the US fast flux test facility. *Journal of Nuclear Materials*, 376(1):47-59.

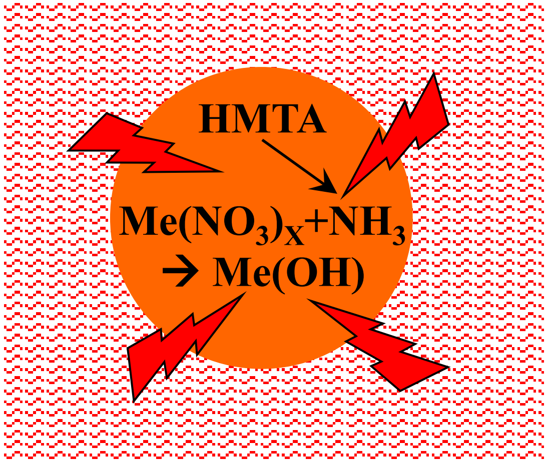
Concet suggested for SFR → GFR, LWR with SiC



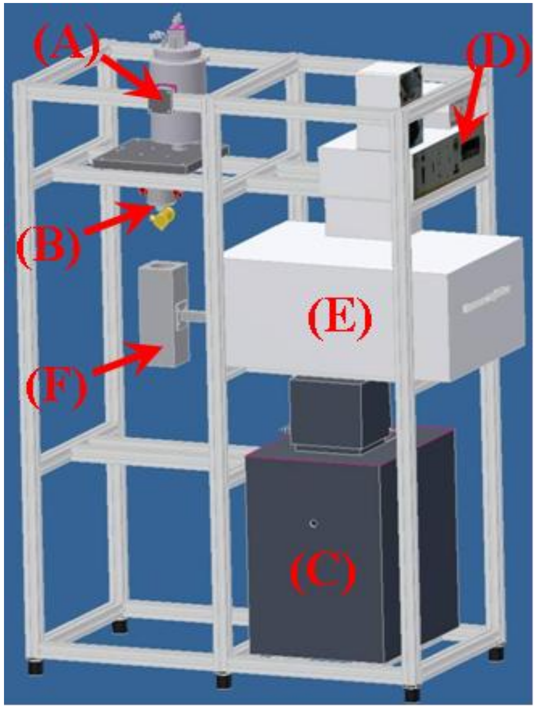


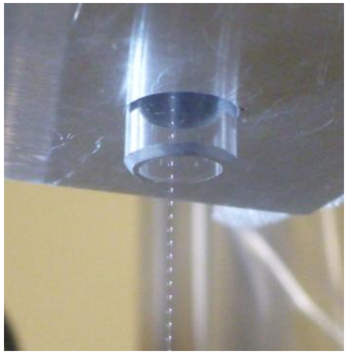


Microwave internal gelation



Internal gelation:
Aqueous process to produce spherical fuel particles (gelation triggered by heat)
→ microwave heating



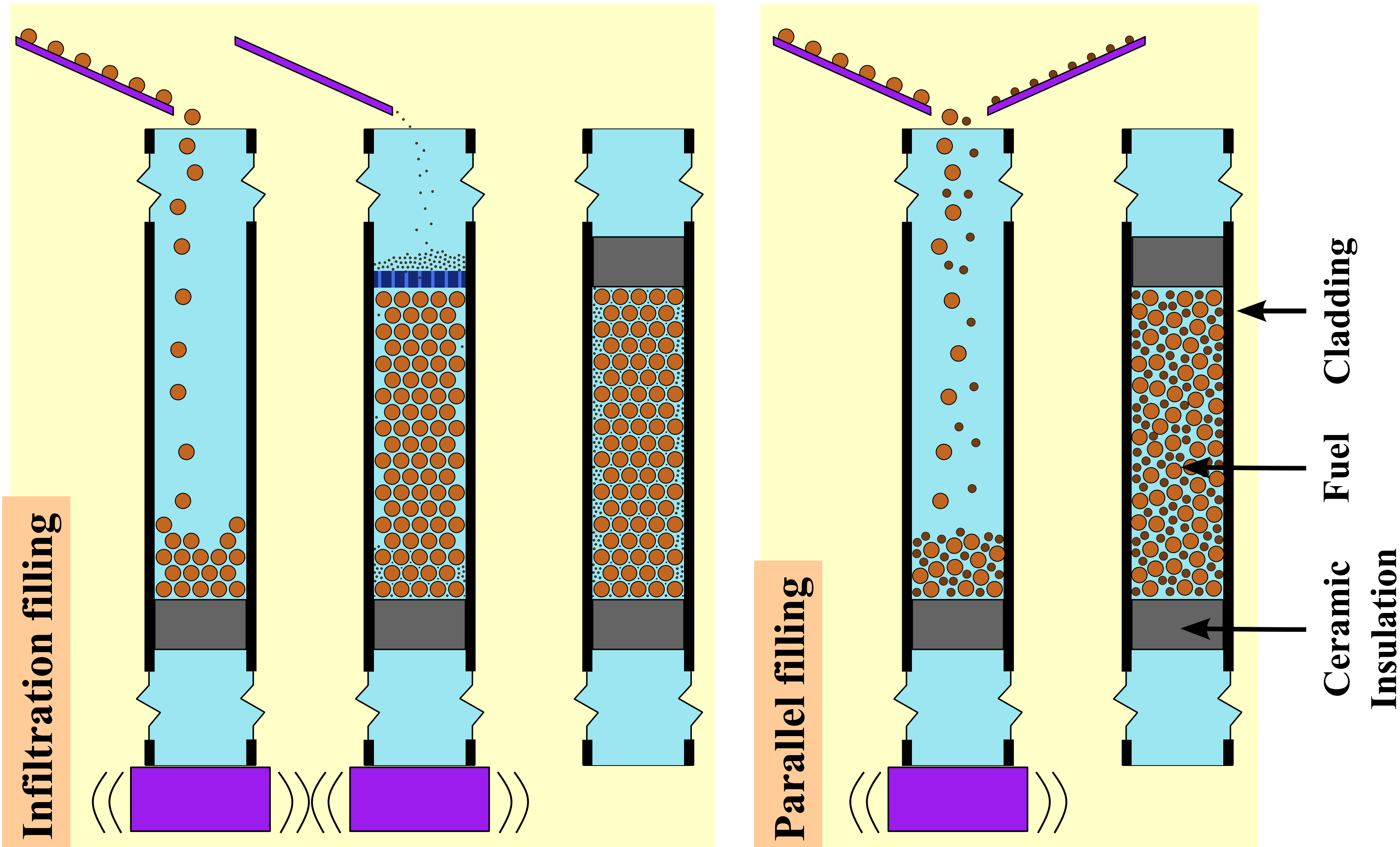


Droplets after cavity:

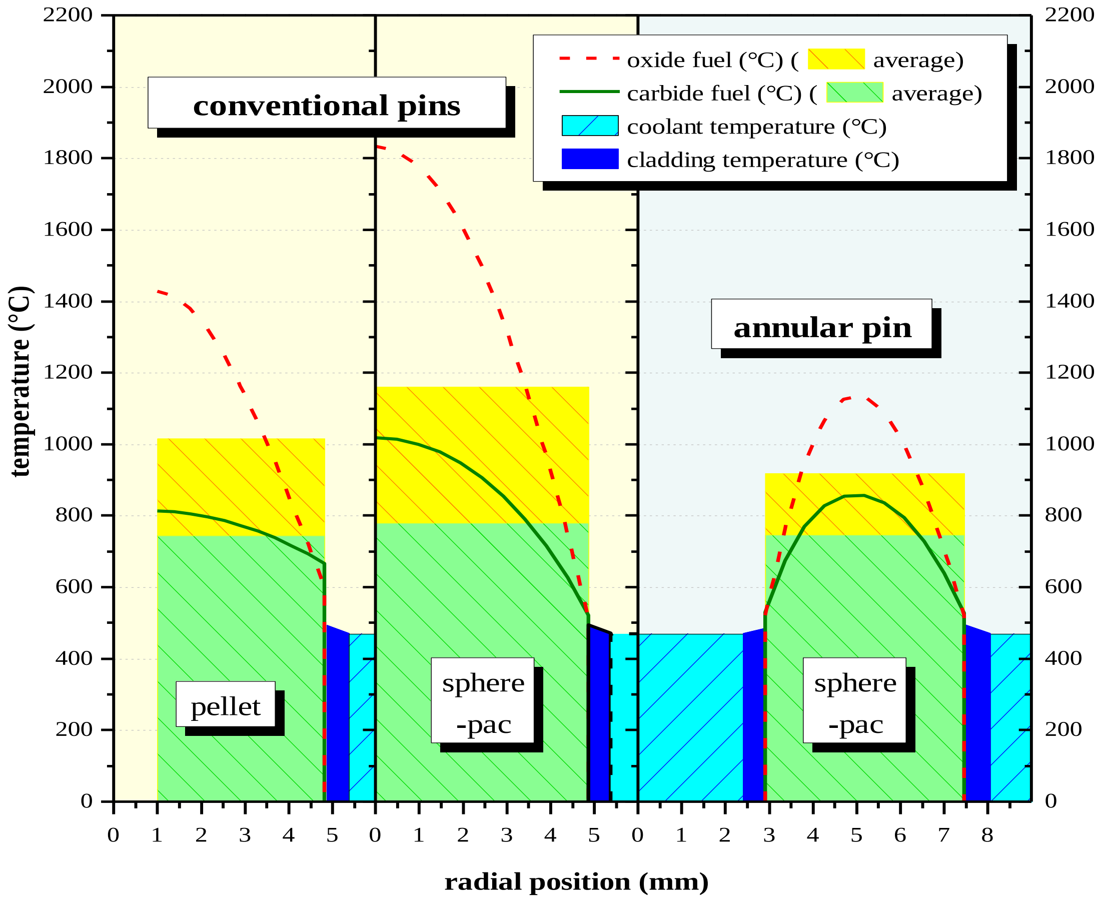
- 14 kHz
- 10 m/s

(A): the feed container,
(B): the vibrator with the nozzle,
(C): the cooling unit,
(D): the control unit for the vibrator,
(E): the microwave unit with the resonant cavity (F)

Filling procedures



Temperature distributions for different concepts

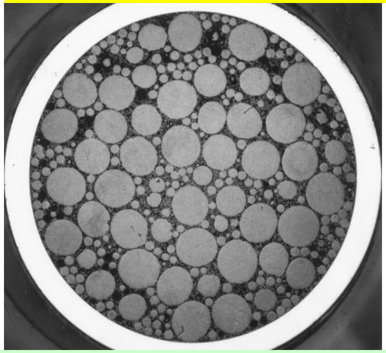


normal 293 W·cm^{-1}, annular 626 W·cm^{-1}

Concept for LWR

- **Sphere-Pac:**
  3 instead of 2 size fractions
  (less room for swelling necessary,
  higher conductivity) →
  total smear density 87% instead of 81 %
- **Hollow Pin:**
  Larger diameter
- **Cladding:**
  SiC/SiC for inner and outer tube.
  (Eventually inner tube as monolithic as only under compression)

1 cycle in PWR (Gösgen)



Nordström, L.-Ã. and Nakamura, M. (2004). (IFA-550.11). In *EHPG-Meeting, Sandefjord Norway, May 2004, OECD Halden Proceedings HPR-362*.

Advantages:

- Easier production (even from reprocessing, similar to DUPIC fuel)
- Allowance for swelling (see fast reactor experience for carbide fuel)
- Lower temp. increase across fuel section (see SFR case)
- Higher cladding surface per fuel volume (4% more, evt. 23% monolithic)
- Higher mechanical stability because of double structure and large diameter

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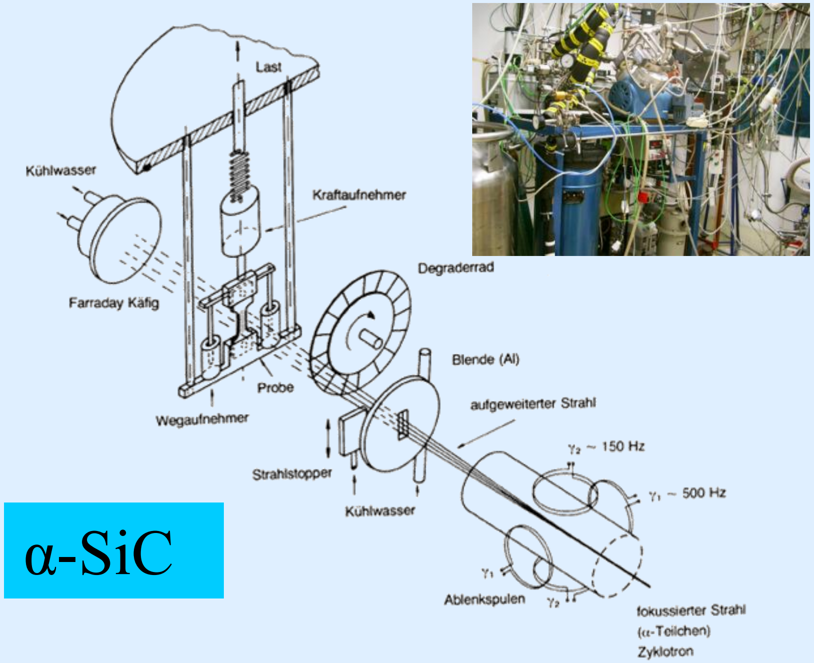
Experimental – Ion and neutron irradiation

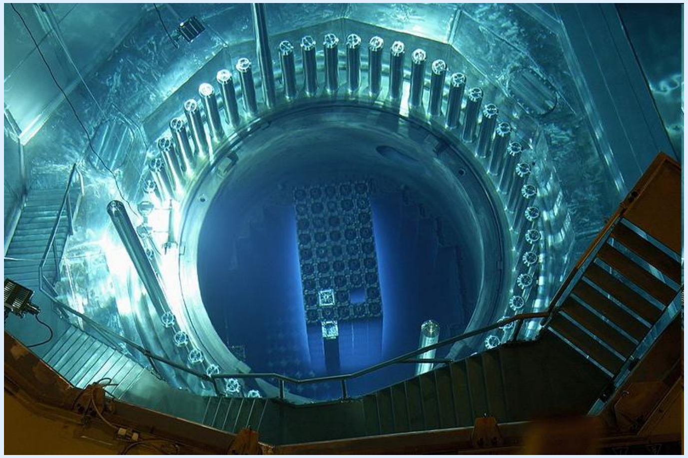
Irrad. with 0-24 MeV He-ions at RT+



α-SiC

sample	He concentration (*appm*)	damage (*dpa*)
Reference	-	-
T3	194	0.012
T7	600	0.036
T8	1500	0.090
T2	2451	0.147

Irradiation temperature: 782-810 °C (Ø 796 °C)

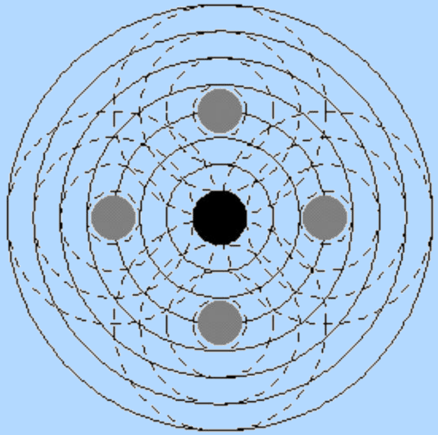


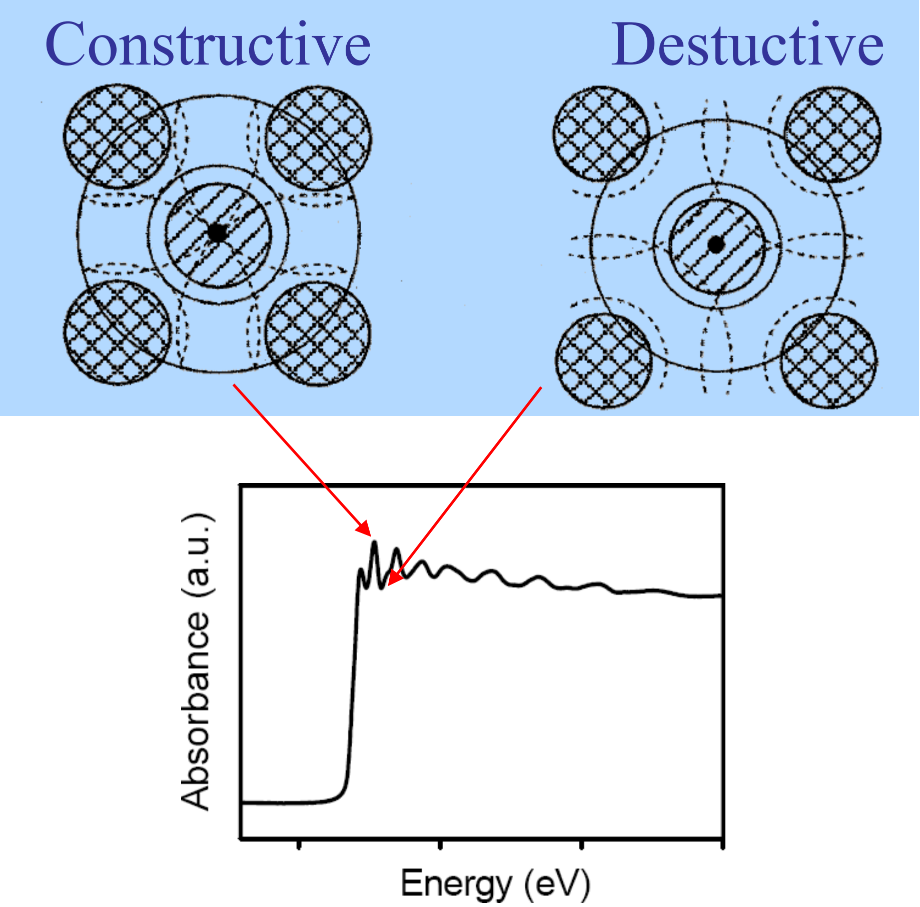
β-SiC

Sample	**Total fluence (>0.1 MeV)** [10^{21} neutrons·cm^{-2}]	**dpa (crosssection SIC-WWSL)** (±15%)
H018	3.39	1.96
H028	3.24	1.87
A032	3.07	1.77
A034	3.33	1.92

What is EXAFS (extended x-ray absorption fine structure)

Selected Atom probing its environment



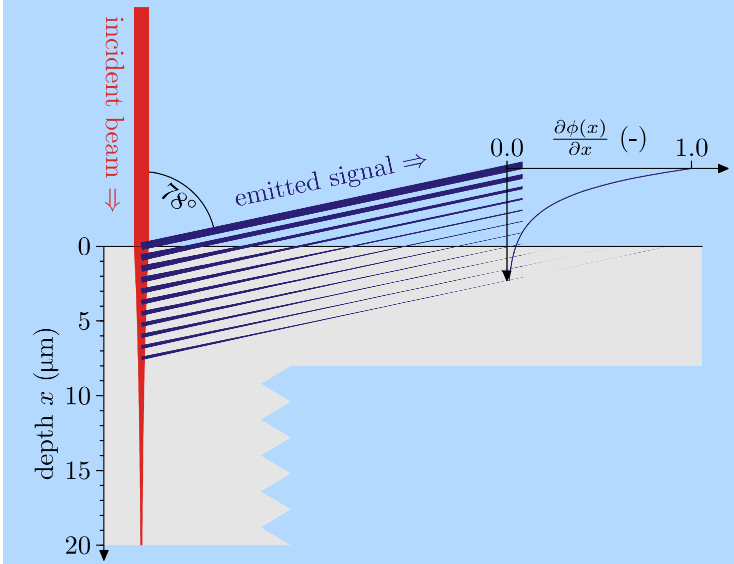


Experiemental - EXAFS

Experiment on **Si** edge

14 28.09
Si
Silicon

K 1s	$L_1 2s$	$L_2 2p_{1/2}$	$L_3 2p_{3/2}$
1839.	149.7	99.82	99.42



Lucia Beamline – SLS

Energy range	0.8 - 8 keV
Flux on sample	2 x 10^{12} ph/s/400 mA
Spot size on sample	1.2 x 1 µm^2
Polarization	linear horizontal
	circular left & right
Photon energy resolution	0.02%

(transferred to Soleil →)

(→ follow up at PSI:)

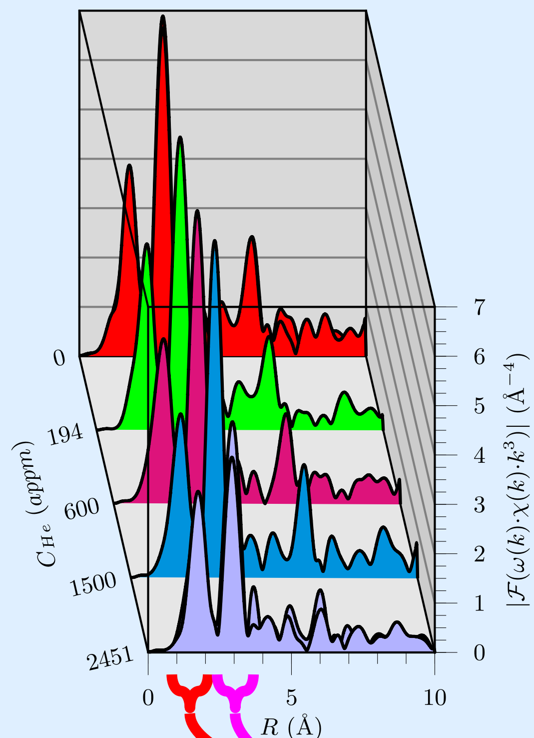
Phoenix Beamline - SLS

0.4 keV to 8 keV

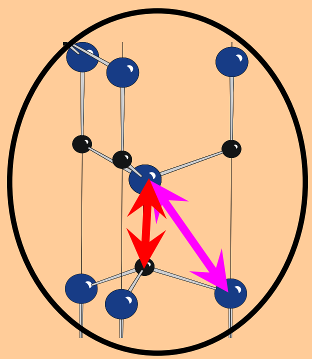
See http://www.psi.ch/sls/phoenix/phoenix-i

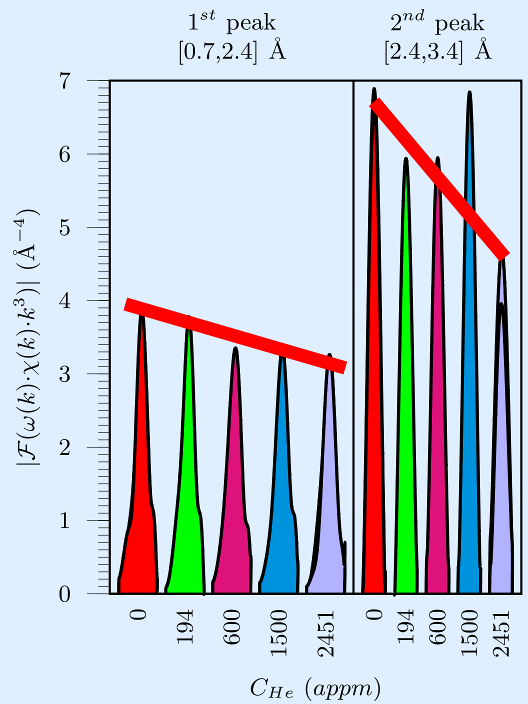
Results – Ion irradiated α-SiC

Measured on Lucia



Result:
Decrease of coordination number in the 1^{st} and 2^{nd} shell (corresponding to Si-C and Si-Si).

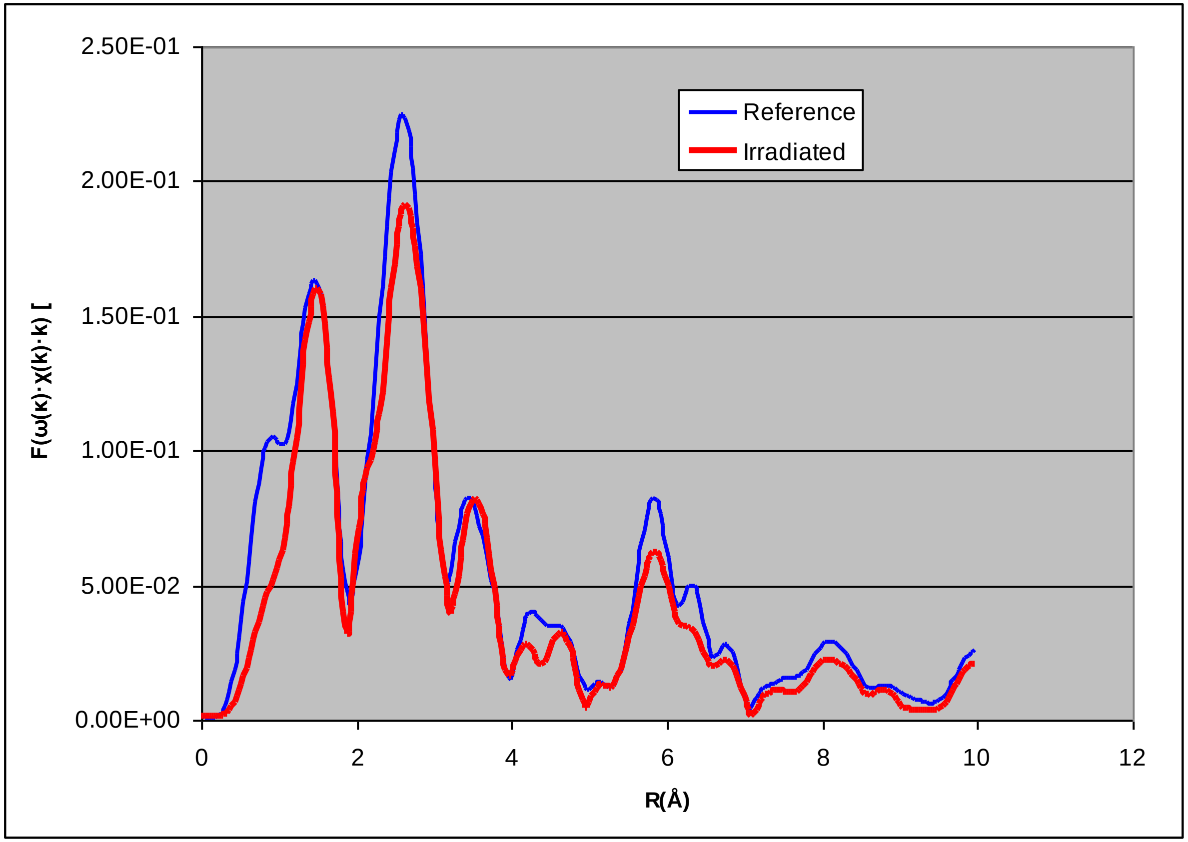


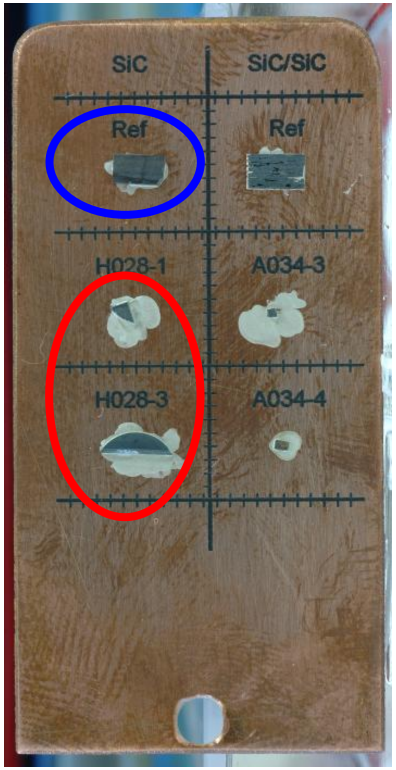


Results – Neutron irradiated β-SiC

Preliminary result from bulk SiC

Measured on Phonenix



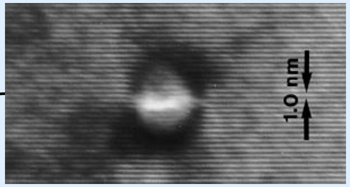


Similar change compared to ion irradiated α-SiC

Modelling – Damage modes

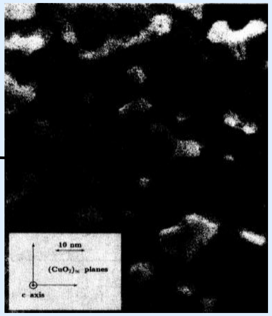
Damage modes

- Crack ← Platelet-formation under He-irradiation (!)

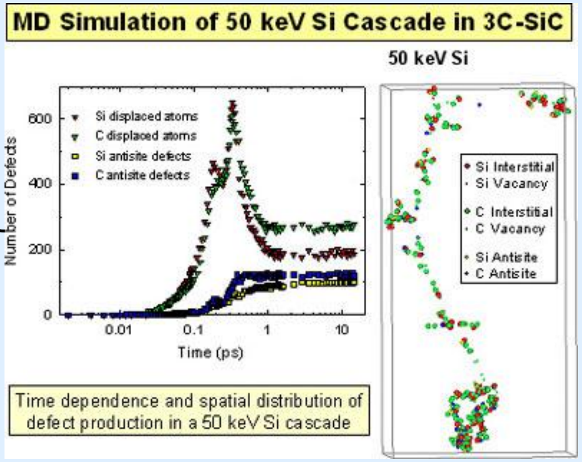


[1]

- Track ← amorphous along ion track (??)


[2]

- Interstitials
- Vacancies



[3]

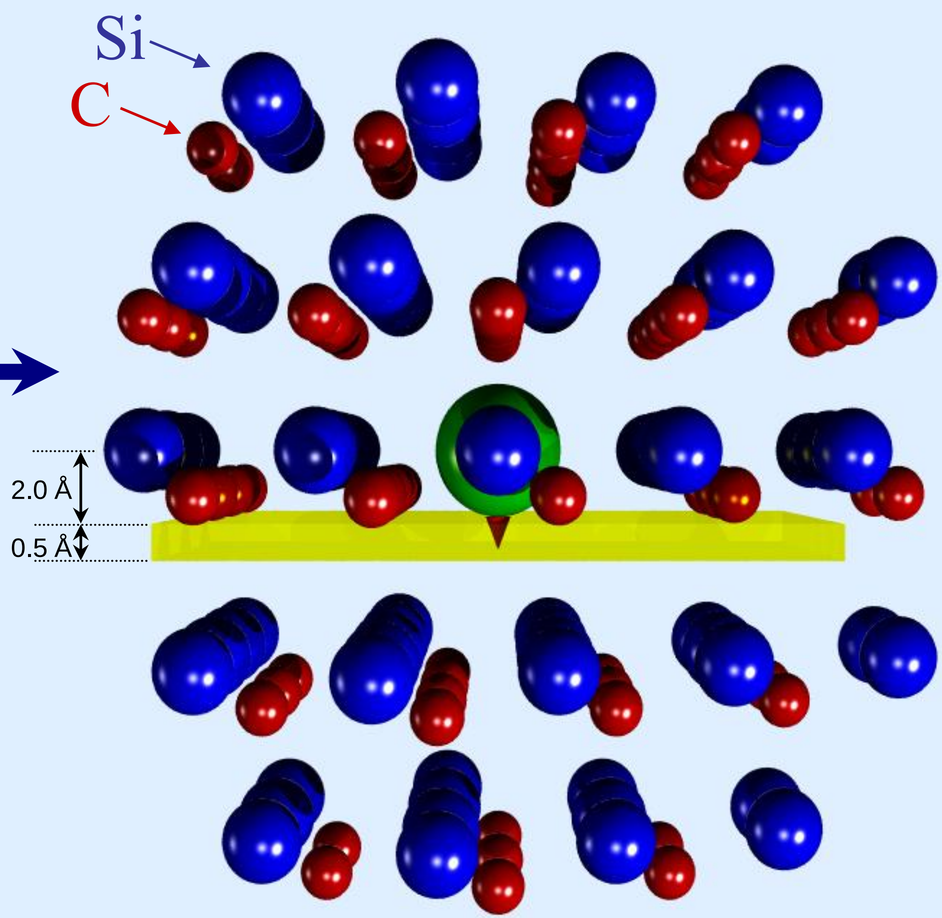
[1] Chen 1999, Phys. Rev. Letters
[2] Hensel 1990, Phys. Rev. B
[3] http://www.emsl.pnl.gov/new/highlights/010404.shtml

Modelling – He platelets

α-SiC

Modelling - Simulation of the EXAFS – Spectra

Structure → Atom Cluster → introduction of damage



FEFF

Atom-clusters

ab initio multiple scattering calculations of XAFS & XANES

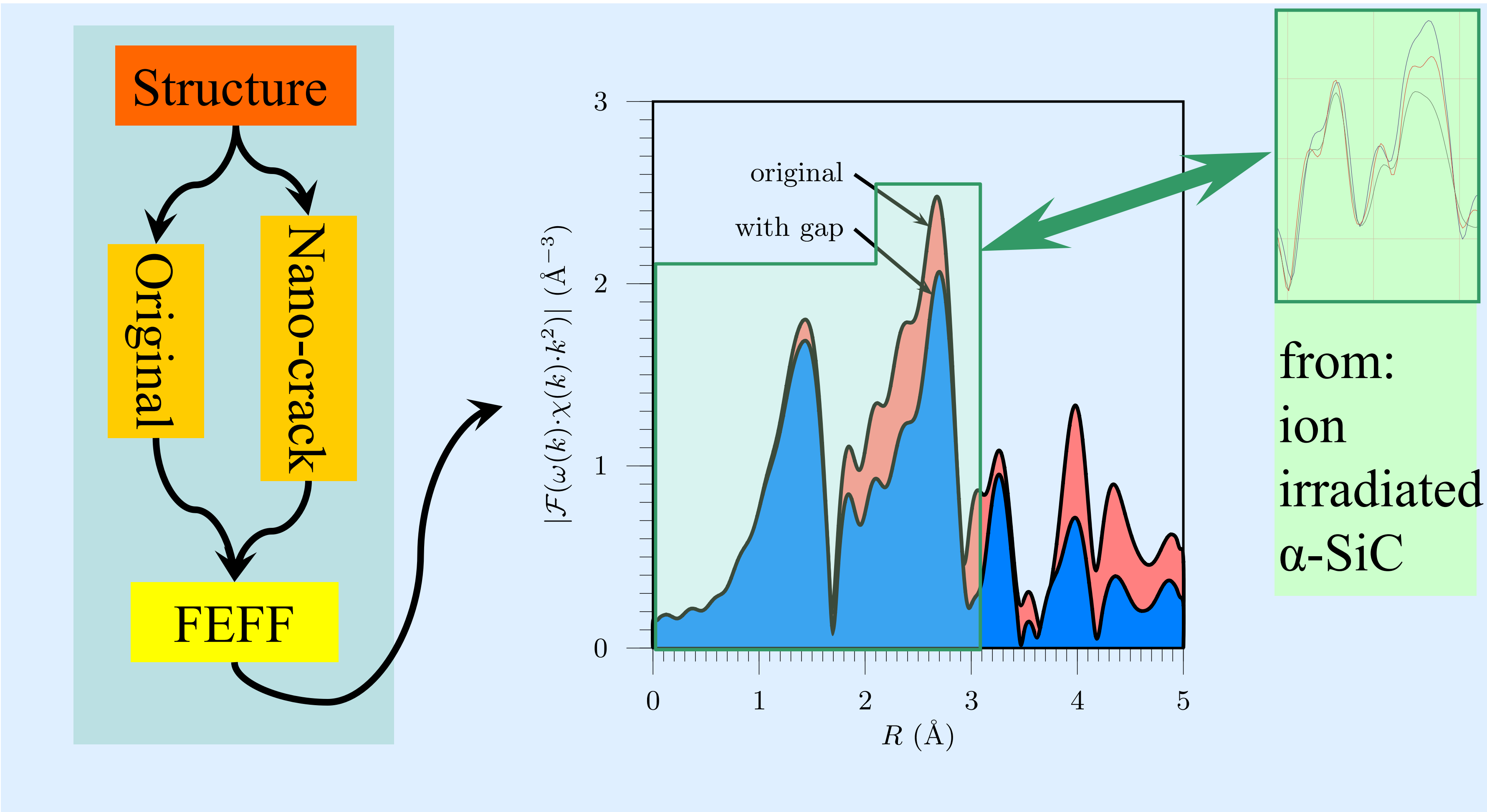
scattering ampl. and phases, …

e.g. EXAFS spectra

Modelling – He platelets

α-SiC

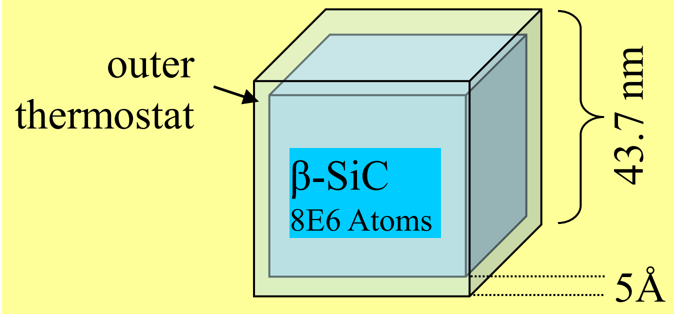
Results - Comparison of Experiment and Simulation

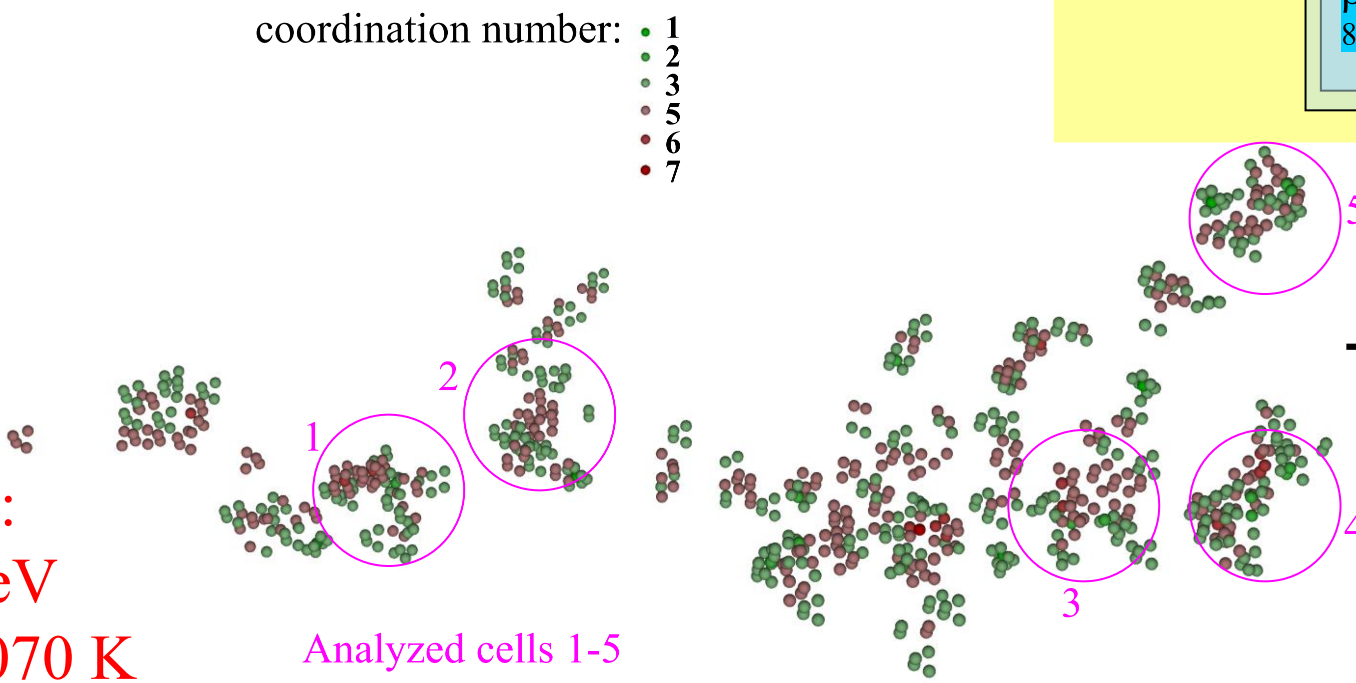


Modellign - Cascade

MD simulation using LAMMPS code
(hybrid Tersoff/ZBL potentials)

Simulation Box



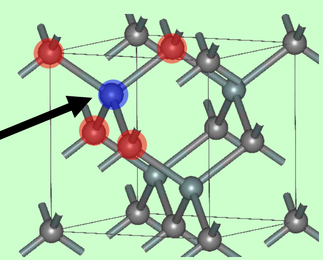


→ 162 Vacancies (Si:C = 5:1)

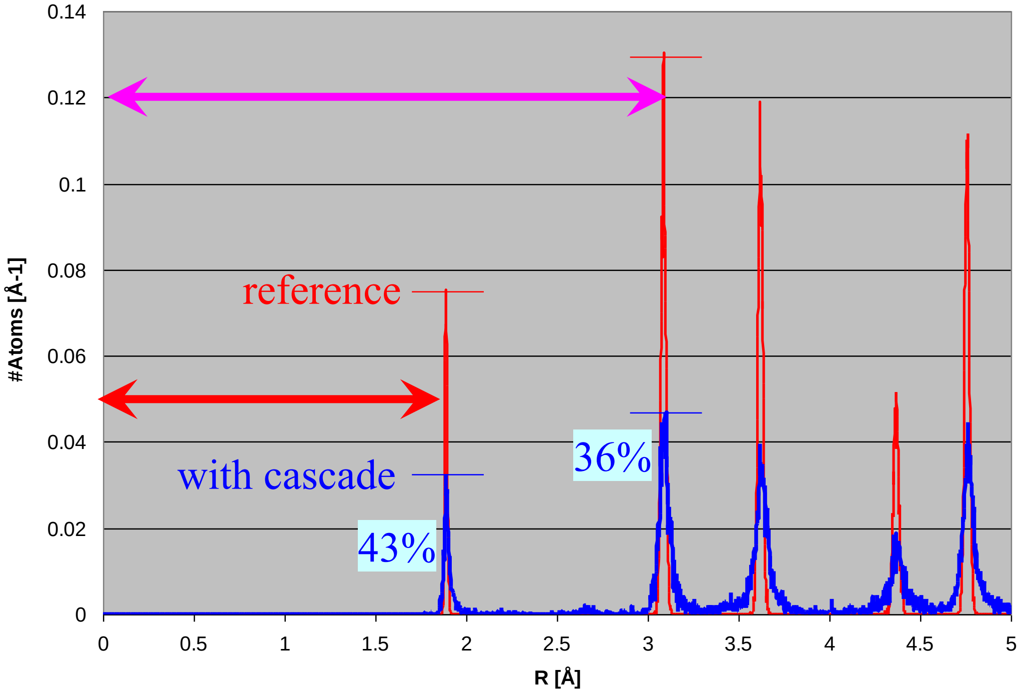
PKA:
10 keV
@ 1070 K

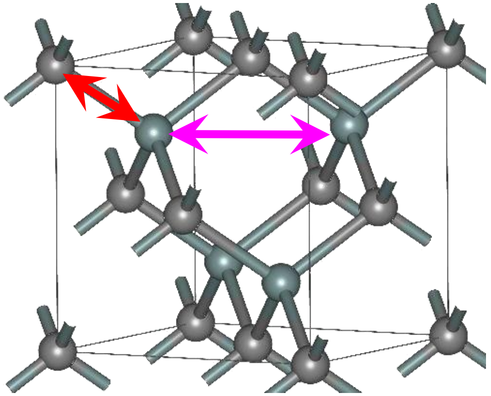
Analyzed cells 1-5

Plot of atoms with coordination numbers ≠ 4
(normal case =4)



Modelling – Cascade





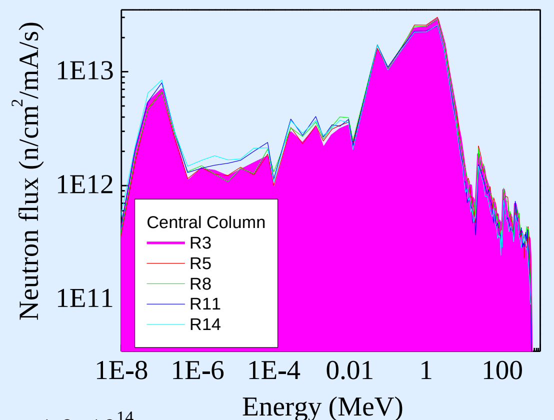
Directly calculated radial distribution function

Only very **initial analysis** with **peak height** at two first neighbors. **First peak shows more important decrease** than in experiment, **second peak decreases stronger, which is compatible with experimental data**

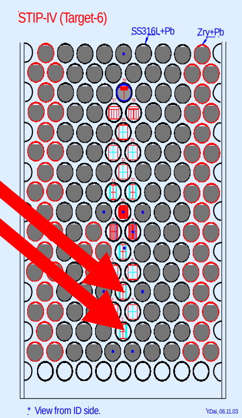
→ Next step is FEFF calculation

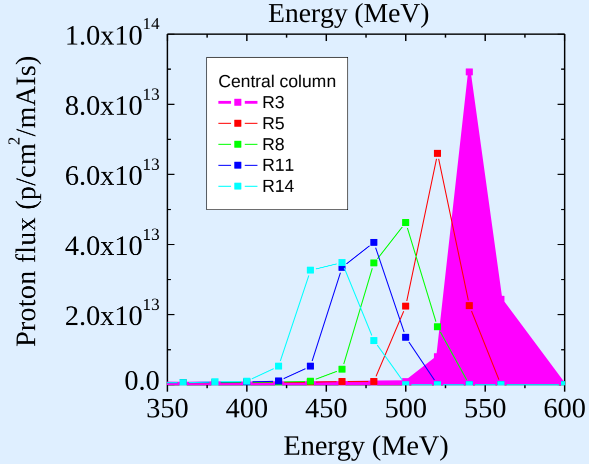
Irradiation at SINQ

Period:	2004.04 $\rightarrow$ 2005.12
Temperature:	up to 700 °C
Max. proton Φ:	~ $6 \cdot 10^{25}$ m^{-2}
Max. neutron Φ :	~ $1 \cdot 10^{26}$ m^{-2}
Proton Energy:	550 MeV
Neutron Energy:	0 $\rightarrow$ 550 MeV



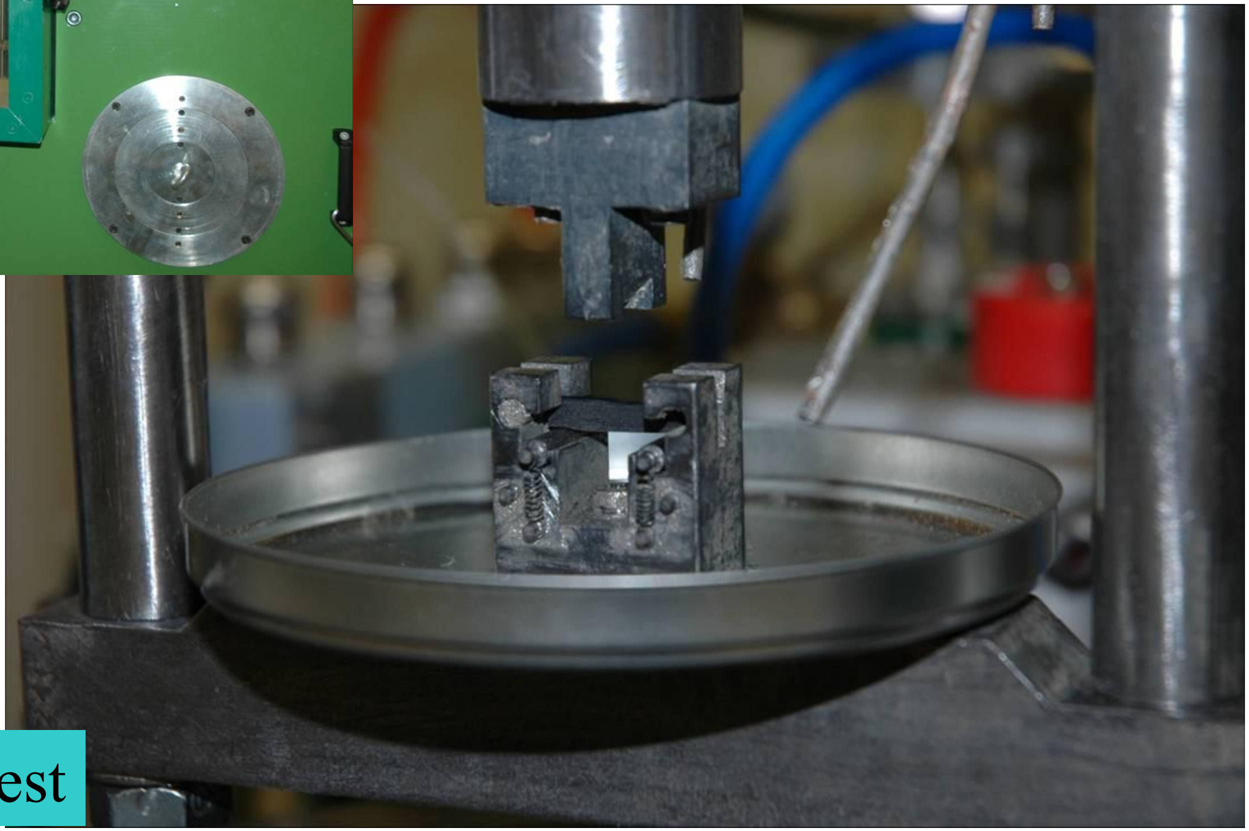
SINQ Target-6





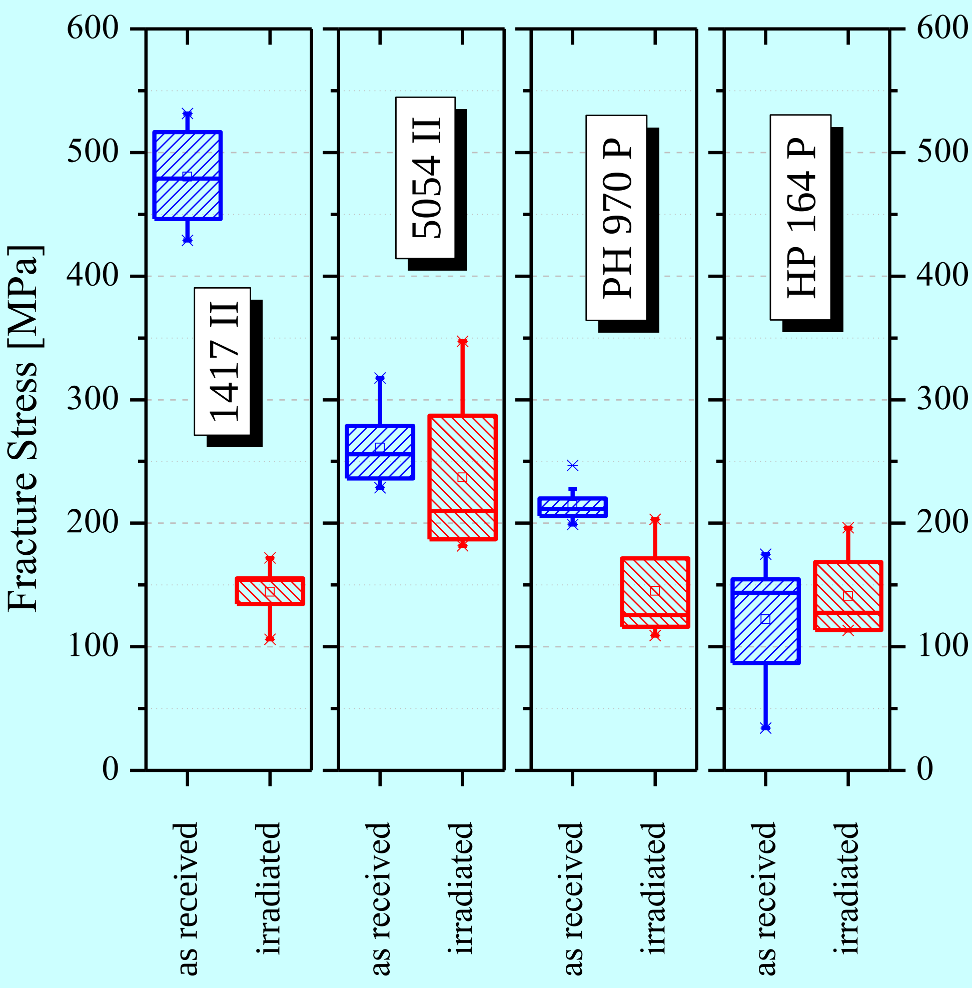
3 Point Bend testing

Hot cell for active samples



Active 3-point bend test

Results of all composite $SiC/(Si)C_f$ bending tests



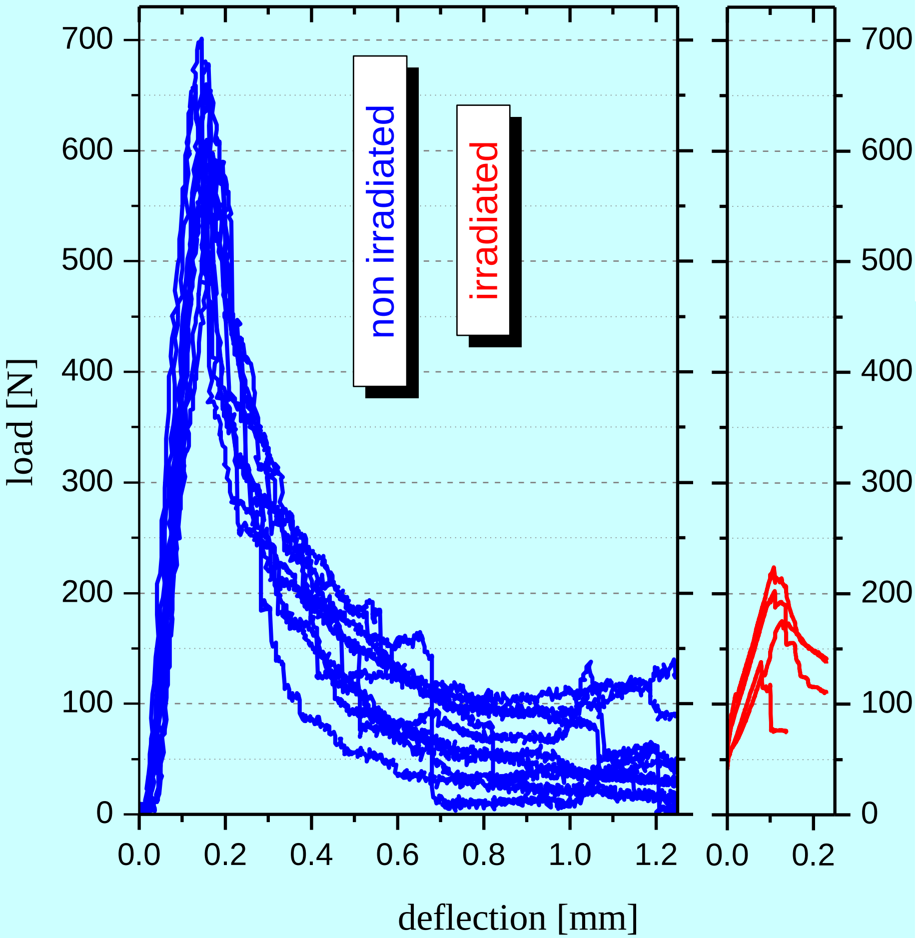
Type of material	Designation	Description
SiC_f/SiC - CVI	1417 II	2D grid, Tyranno™ fiber
C_f/SiC - CVI	5054 II	2D grid, amorphous fiber
C_f/SiC - LSI	PH 970 P	2D grid, amorphous fiber
C_f/SiC - LSI	HP 164 P	irregular fibers, amorphous fiber

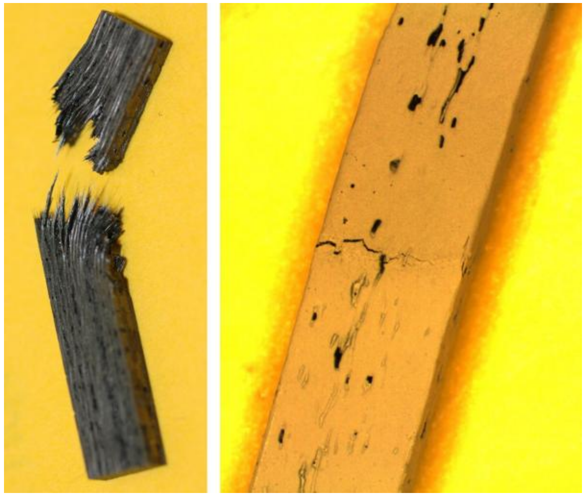
LSI:
Deutsches Zentrum für Luft- und Raumfahrt (DLR)
CVI:
MT Aerospace AG

Results before and after irradiation

SiC/SiC – Mechanical testing

Bad example for old SiC fiber type





Bend-test before
and after irradiation

Non-nuclear Tyranno fiber:
substantial amount of oxygen and excess carbon
→ irradiation-induced **densification**
→ **New:** near-stoichiometric, polycrystalline SiC

Conclusions Hollow Pin Concept

- **Easy, dustless production of SP fuel**
- **Mechanical advantages**
- **Higher cooling surface (compatible with SiC)**
- **Promising first calculation results of hollow pin performance for SFR**

Conclusions SiC investigations

- **Investigations leading to understanding of SiC basic damage mode under irradiation**
- **Mechanical testing leading to understanding of different fiber types in SiC based composites**