PAUL SCHERRER INSTITUT

NUCLEAR ENERGY AND SAFETY

Dynamics of irradiation-induced defects in nuclear materials: a proposed energetic-ion pump - X-ray FEL probe experimental approach

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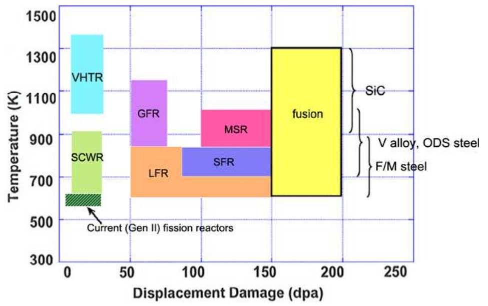
Context of the study

- Nuclear reactor types with specific operating conditions [1]:



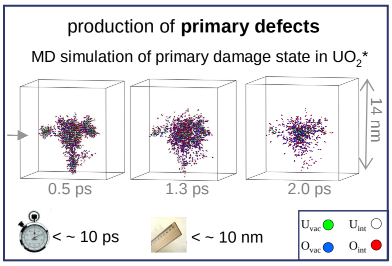
demanding operating conditions:	current Gen. II systems	future Gen. IV systems
▪ temperature	~ 300 - 400 °C	up to 700 °C
▪ dose$_{cladding}$	~ 20 dpa	up to 200 dpa
▪ fuel burnup	~ 60 MWd/kg	~ 200 MWd/kg

Irradiation damage is and will be – in the future – a safety-relevant issue.

Motivation of the study

Understanding of:

- temporal evolution of the primary stage of the irradiation-induced damage in nuclear materials (e.g. cladding materials (Zr-alloys), reactor pressure vessel (RPV) steels, ceramics, composite materials) [2]



diffusion and **reactions** of defects
e.g.

- clustering
- annihilation at sinks
- interaction with foreign atoms

> ~ 10 ps   > ~ 10 nm

* from F. Devynck & M. Krack (LRS / NES / PSI))

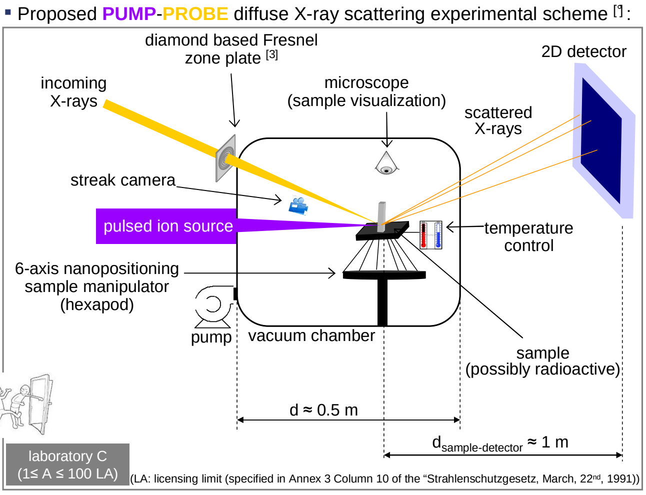
- impact on the materials microstructure

→ Irradiation can induce modifications of the materials properties – e.g. irradiation-induced hardening and embrittlement, irradiation-induced high temperature creep, irradiation-induced swelling – and dimensions.

Proposed experiment

▪ Sketch of the experiment

▪ Proposed **PUMP-PROBE** diffuse X-ray scattering experimental scheme [*]:



[*] common scientific interests with B. Larson and co-workers (Oak Ridge National Laboratory) and with T. Cowan and co-workers (HZDR).

▪ Expected results

- statistics of the formation of the primary interstitials and vacancy defects, and their nanometer sized clusters
- evolution of their structure, distribution and mobility
- diffusion rate of the vacancies and interstitials clusters

- experimental validations of MD simulations
- possible development of advanced irradiation-resistant materials

▪ Key parameters of the experiment

Parameter		Unit	Requirement	Motivation / Remarks
▪ Key parameters of the X-ray FEL radiation				
Energy		keV	5 - 20	X-ray diffuse scattering
	stability			
Bandwidth		%	~ 0.05	
	stability		< ± 10% bw	
Position	stability	nm	< 100	stable incoming beam is wished
Size		nm	~ 200	
Photons / pulse		#ph	~ 10^{11}	
	stability	%	± 10	
Pulse duration		fs	≤ 50	
	stability			
Pulse arrival time	stability	fs	~ 200	
▪ Beam parameter changes during experiment				
Energy	range / step	eV	< 1	use of high-brightness seeded pulses: possible additional approach: stack of coherent diffraction patterns recorded at an absorption edge, i.e. elemental specificity (e.g. Zr, Nb, Y, Am, … for E_{photon} > 12 keV)
	rate	eV/min		
Size	range / step	µm	- - -	
	rate		- - -	
Pulse length	range/step		- - -	
	rate		- - -	
▪ Beam geometry				
Slope		µrad	---	
Working distance		mm	~ 250	minimum required
▪ Other				
Diamond-based Fresnel zone plate			yes	focusing of hard X-rays down to ~200 ×200 nm² spot size at the sample surface (C. David, LMN / PSI, [3])
Transverse coherence			yes	required for coherent X-ray diffraction
Laboratory C			yes	sample activity (A): 1 ≤ A ≤ 100 LA, with LA: licensing limit)

Ion source (laser-accelerated high-energetic ion source*)

Ion energy	keV	10 - > 1000	
Particle type	element	e.g. Cs, I, Fe, Kr, Xe, He, H	
Single/multiple ion(s)		yes	adjustable fluence
Arrival time synchronization	ps	< 1	

*Interested partners: J. Ullrich, R. Moshammer (MPI Heidelberg, Germany)

References

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[2] A. Froideval et al., J. Nucl. Mater. 416 (2011) 242-251.
[3] C. David et al., Scientific Reports 1, 57 (2011); DOI: 10.1038/srep00057.

Acknowledgments

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