CORE 2025

PROJECT KOMÁR

Konštrukčné materiály jadrových zariadení
(Structural materials of nuclear facilities)

IDENTIFICATION OF EARLY STAGES OF RADIATION DAMAGE BY POSITRON ANNIHILATION TECHNIQUES

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OUTLINE

1 ABOUT THE PROJECT

2 STUDIED MATERIALS

3 METHODOLOGY (Neutron irradiation, Proton implantation, PAS)

4 RESULTS (T91 vs. SIMP vs. ODS Eurofer, FeCrAl vs. Fe)

ABOUT THE PROJECT

- study of **early stages** of radiation damage in perspective materials with applications in modern nuclear facilities
- materials: **F/M steels** (T91, SIMP, ODS EUROFER) & **ferritic alloys** (FeCrAl alloy, Fe5Cr) + pure Fe
- **neutron** irradiation (CVŘ) & **proton** implantation (MTF STU) – addressing the application of ion implantation as a surrogate for neutron-induced damage
- **positron annihilation** characterization of microstructure (INPE) – study of vacancy-type defects

STUDIED MATERIALS

Tab.1 Chemical composition of studied materials in wt %.

Material	Mn	P	Si	Al	Ti	Cr	Ni	Cu	C	N	V	Mo	Nb	Y	Zr	W	Ta	Fe
T91	0.38	0.009	0.43	-	-	**8.26**	0.13	-	0.105	0.0055	0.20	0.95	0.075	-	-	-	-	89.5
SIMP	0.52	0.004	1.22	-	-	**10.24**	-	-	0.22	-	0.18	-	0.01	-	-	1.45	0.12	86.04
ODS EU	0.44	-	0.05	-	-	**8.9**	-	-	0.1	0.04	0.2	0.03	0.002	0.3	-	1.1	0.14	88.7
FeCrAlloy	-	-	-	5	-	**22**	-	-	-	-	-	-	-	0.1	0.1	-	-	72.8
Pure Fe	-	-	-	-	-	**-**	-	-	-	-	-	-	-	-	-	-	-	100
Fe5Cr	0.02	0.011	0.006	0.003	0.003	**5**	0.06	0.01	0.02	0.034	0.001	-	-	-	-	-	-	94.8

METHODOLOGY

Neutron Irradiation

LVR-15 (Research Centre Řež)

Avg. Temperature: **260 ± 20 °C**
Damage: **0.12 dpa**
Total Fluence: 4.94 x 10^{20} cm^{-2}
Time: 101 effective days

Tab.2 Neutron energies and respective fluences.

Neutron energy	Fluence ($n.cm^{-2}$)
< 0.5 eV	1.28E+20
0.5 eV - 110 keV	1.96E+20
0.11 - 20MeV	1.69E+20
> 0.5 MeV	1.13E+20
> 1 MeV	7.37E+19
Total	**4.94E+20**

Tab.3 KOMÁR irradiation cycles.

Sample block	Sample designation	Stabilized irradiation temperature per irradiation cycle (°C)				
		K214	K215	K216	K217	K218
B2	KOMAR	248.0 – 260.6	158.1 – 170.1	271.0 – 275.0	267.5 – 274.5	267.5 – 272.5
Irradiation time percentage in each cycle		17.41%	4.63%	30.30%	24.47%	23.20%

Courtesy of M. Mikloš & J. Šoltés

METHODOLOGY

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Tab.4 Cycle K214 description.

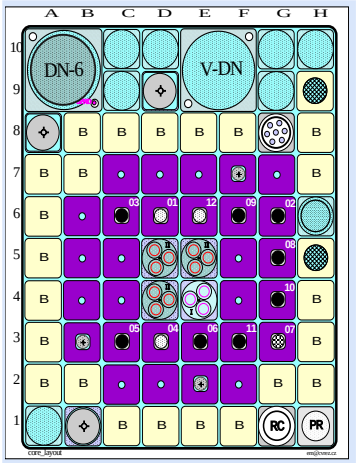
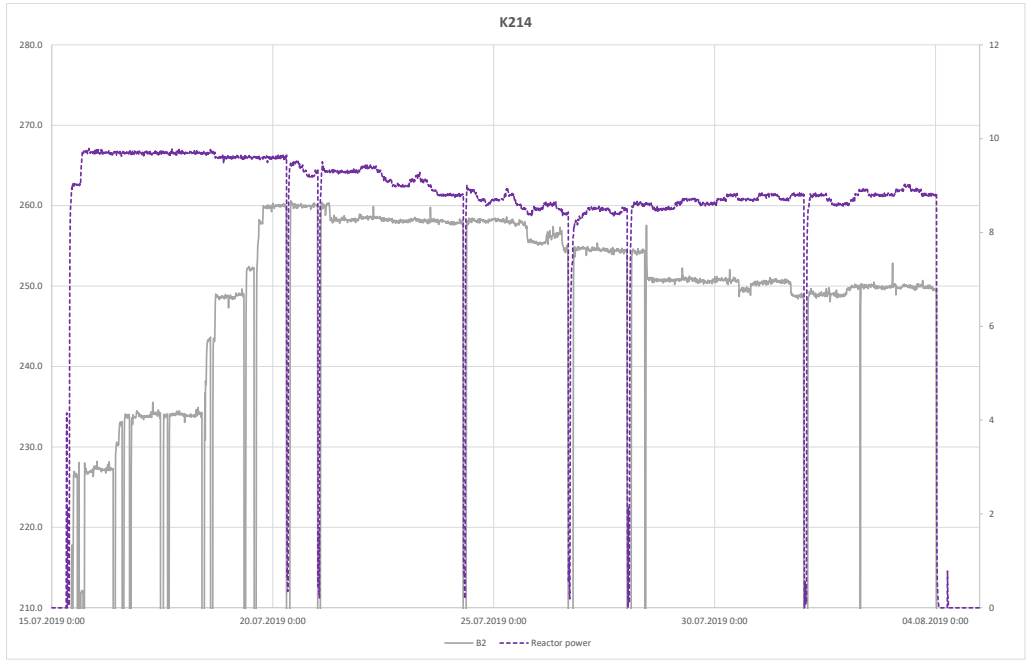
	Cycle K214
Rig position	G8
Reactor Core Configuration	
Irradiation Length [hours]	471.67
Reactor Power [MW]	8.2 – 9.7
Effective Days (for 10 MW)	17.4

Fig.1 Cycle K214 reactor power.



Courtesy of M. Mikloš & J. Šoltés

METHODOLOGY

Proton
Implantation

6 MV Tandetron (Faculty of Materials Science and Technology in Trnava)

Temperature: **RT** & **300 °C**
Damage: **0.0196 dpa**
Total Fluence: 6 x 10^{16} cm^{-2}
Time: 16.67 hours
Energy: 5 MeV

Fig.2 Implantation profile.

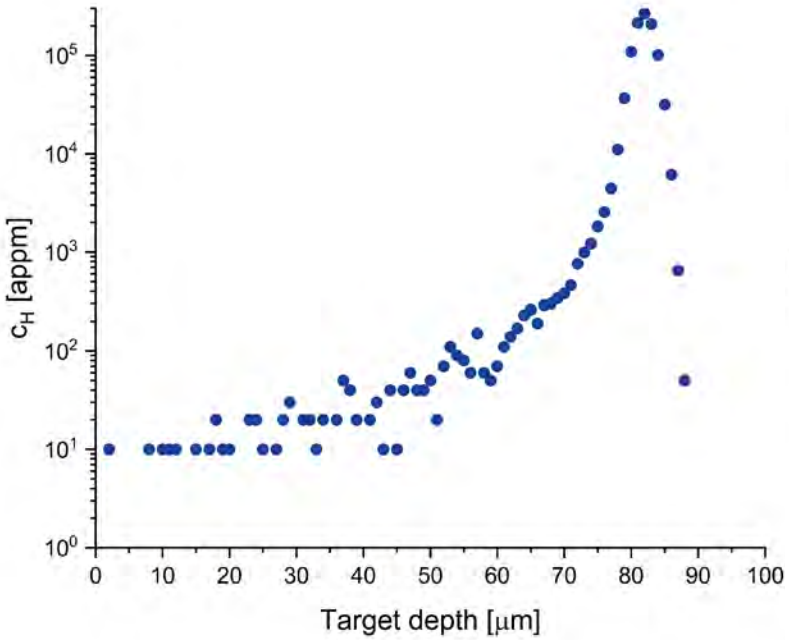
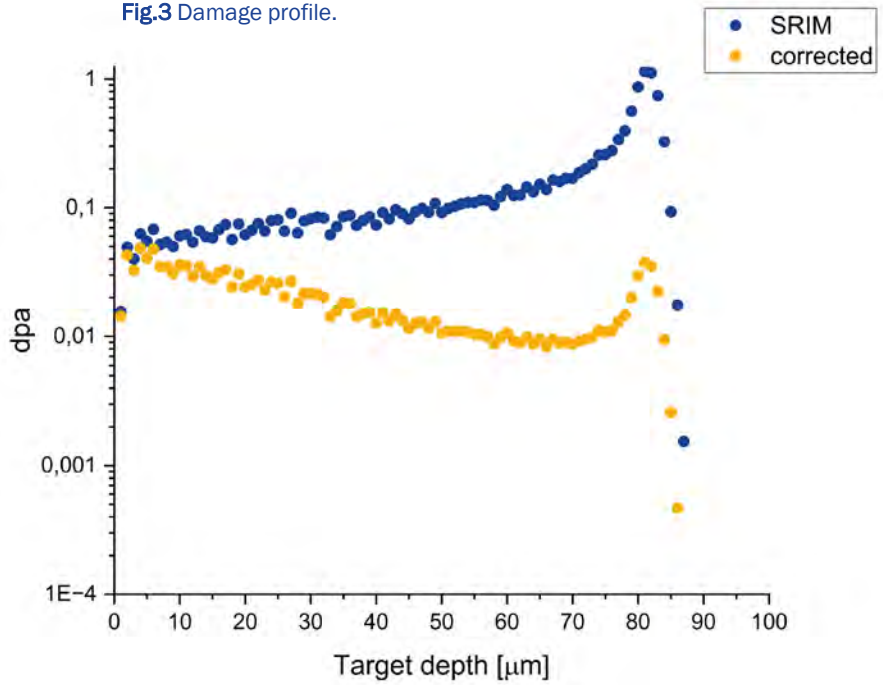


Fig.3 Damage profile.



METHODOLOGY

PAS
(Positron Annihilation Spectroscopy)

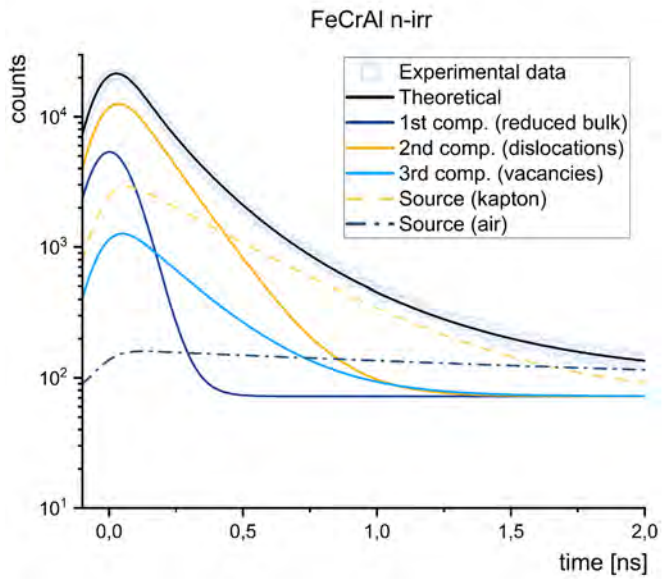


Fig.4 PAS lifetime spectrum of irradiated FeCrAl.

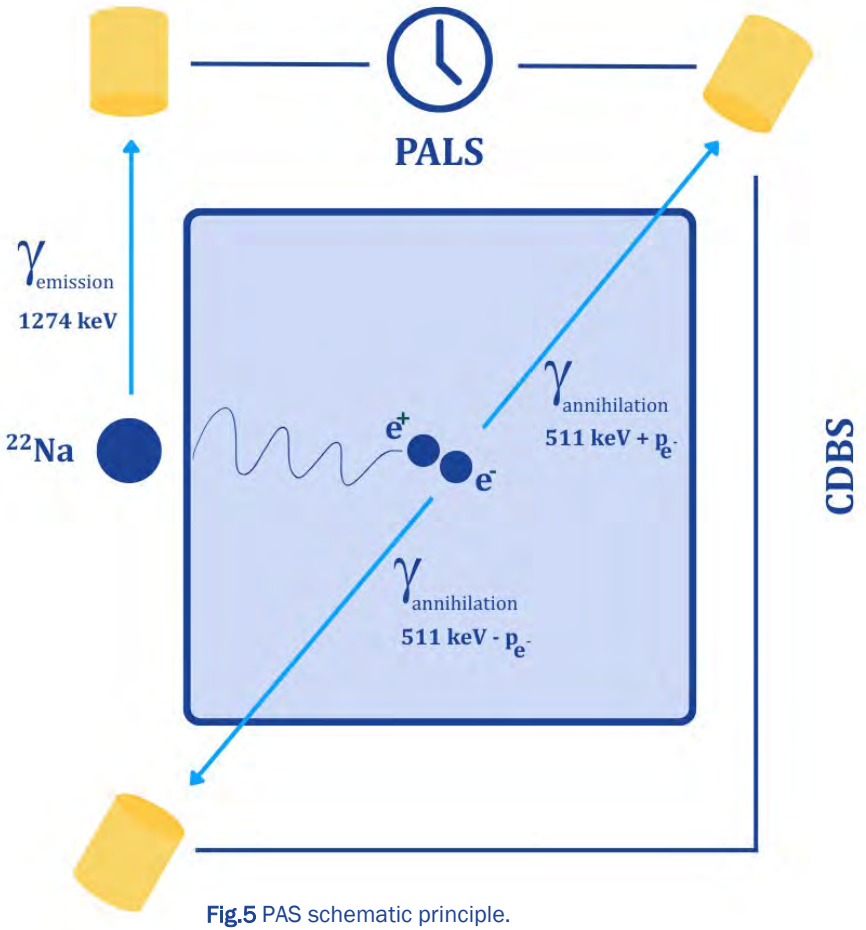


Fig.5 PAS schematic principle.

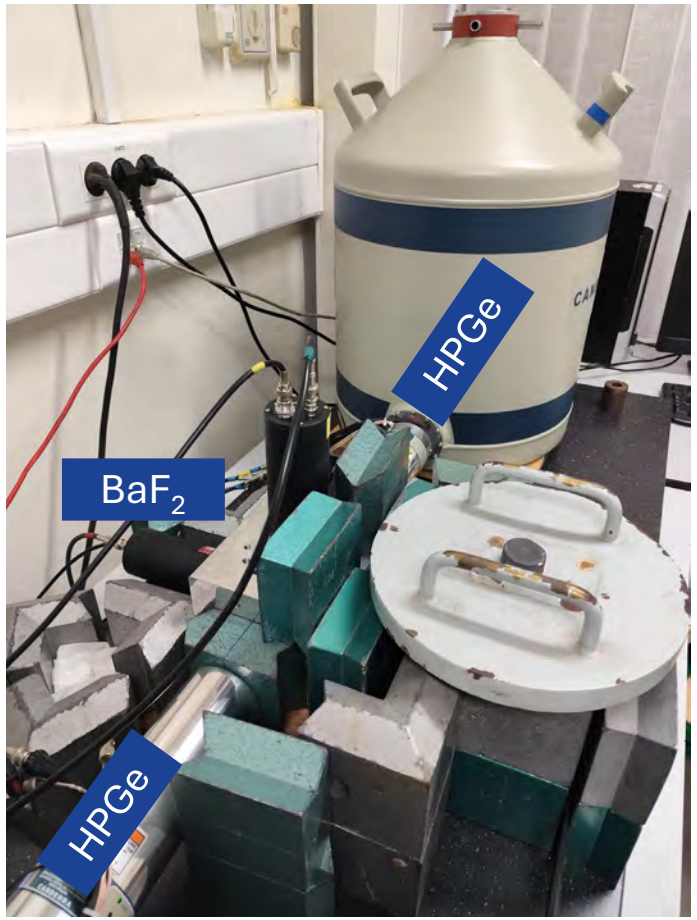


Fig.6 PAS equipment at the INPE laboratory.

RESULTS

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Positron annihilation spectroscopy evaluation of using proton irradiation as a surrogate for early neutron radiation damage

Sofia Gašparová, Vladimír Kršjak, Pavol Noga, Jaroslav Šoltés, Marek Miklos, Yamin Song, Martin Petriska, Stanislav Sojak, Dušan Vaňa, Zoltán Száraz, Branislav Stríbrnský, Róbert Hinca, Tielong Shen, Jarmila Degmová

Presented at APCOM 2025

Evaluating Proton Irradiation for Simulating Early Neutron Damage in F/M Steels Using Positron Annihilation Spectroscopy

Sofia Gašparová[1,a)], Vladimír Kršjak[1], Yamin Song[1], Pavol Noga[2], Jaroslav Šoltés[3], Marek Miklos[3], Martin Petriska[1], Stanislav Sojak[1], Dušan Vaňa[2], Zoltán Száraz[2], Branislav Stríbrnský[1], Róbert Hinca[1], Tielong Shen[4], and Jarmila Degmová[1]

T91 vs. SIMP vs. ODS EUROFER

- ODS shows highest stability after irradiation/implantation
- p, LT condition – profound increase (H stabilisation of vacancies)
- p, HT condition – recombination overweighs production

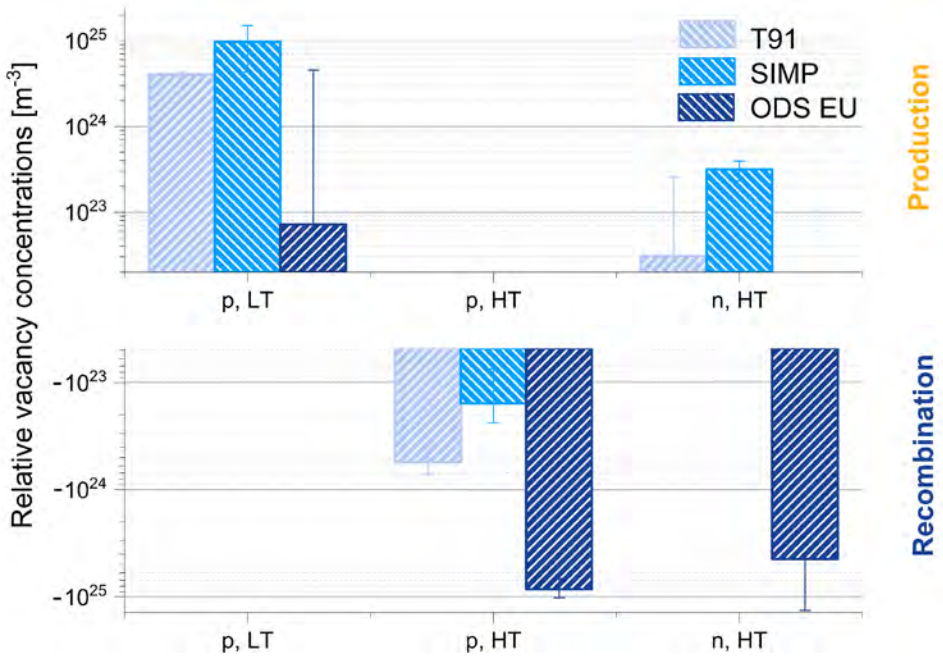


Fig.7 Relative vacancy concentration comparison of T91, SIMP and ODS EU.

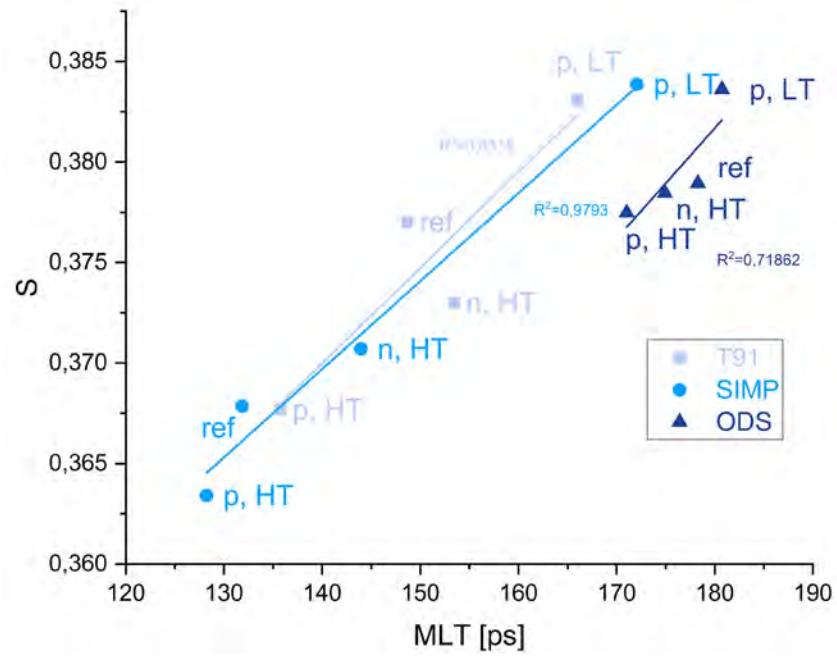


Fig.8 S parameter vs. MLT comparison of T91, SIMP and ODS EU.

RESULTS

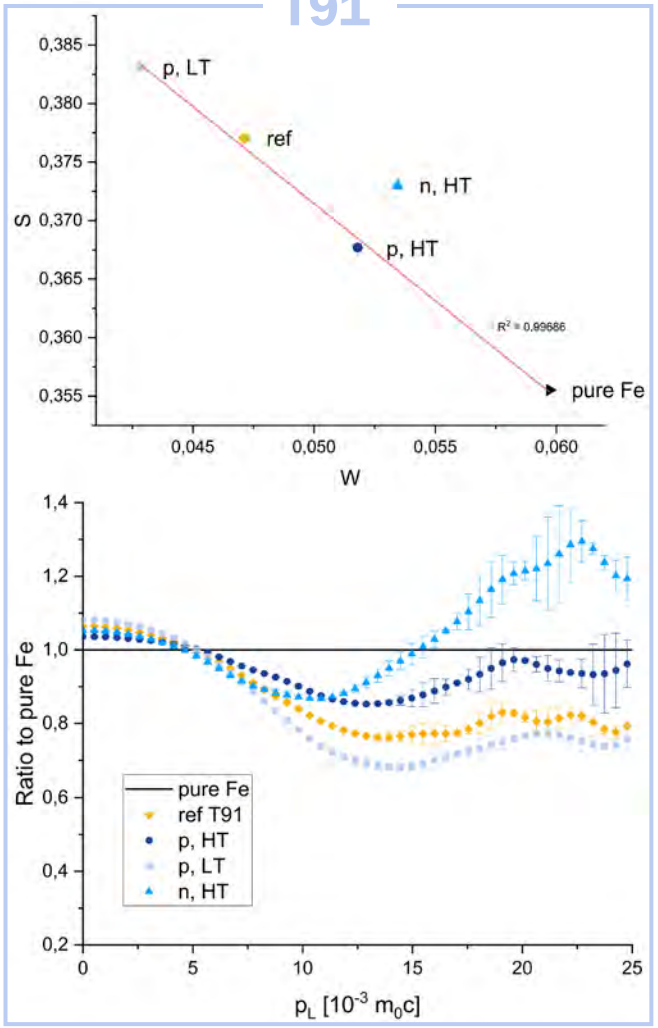
T91

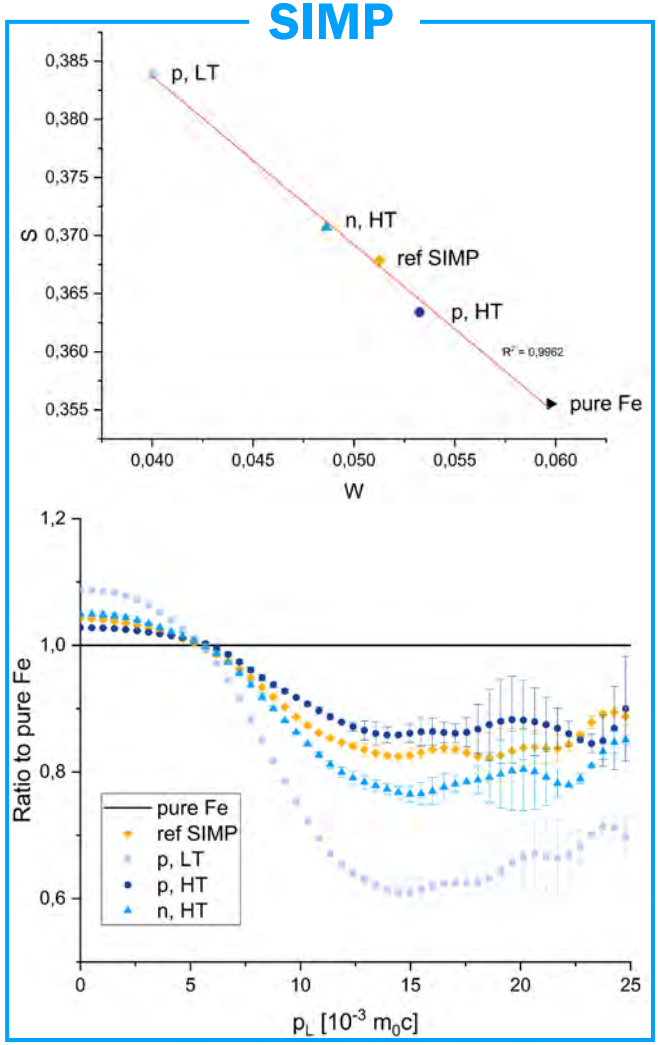
vs.

SIMP

vs.

ODS EUROFER





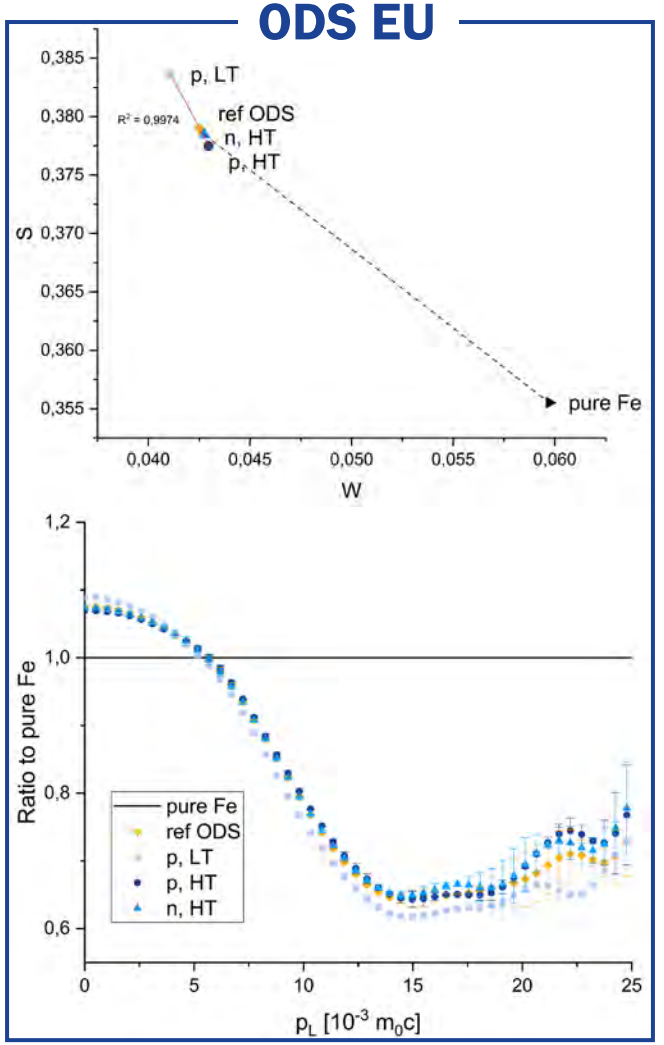
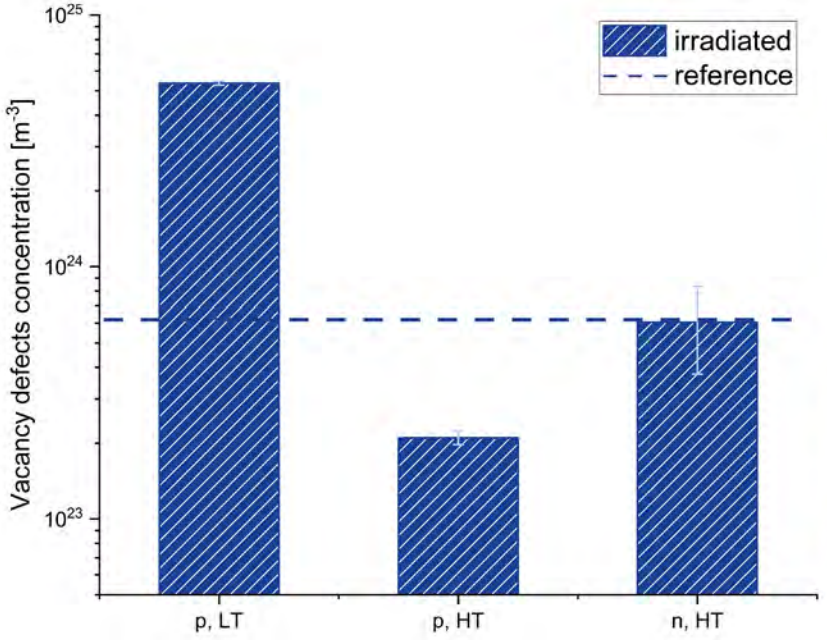


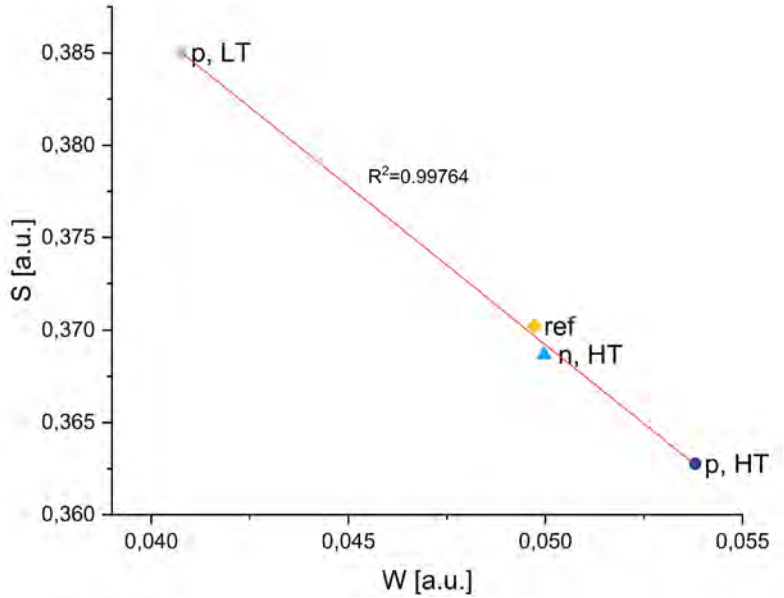
Fig.9,10,11 The CDBS S-W results and momentum curve of T91, SIMP and ODS EU steel before and after irradiation.

RESULTS

FeCrAl

- Similar trend across irradiation conditions
- Profound production of defects at low-temperature implantation
- S-W plot suggests similar type of defects





Production

Recombination

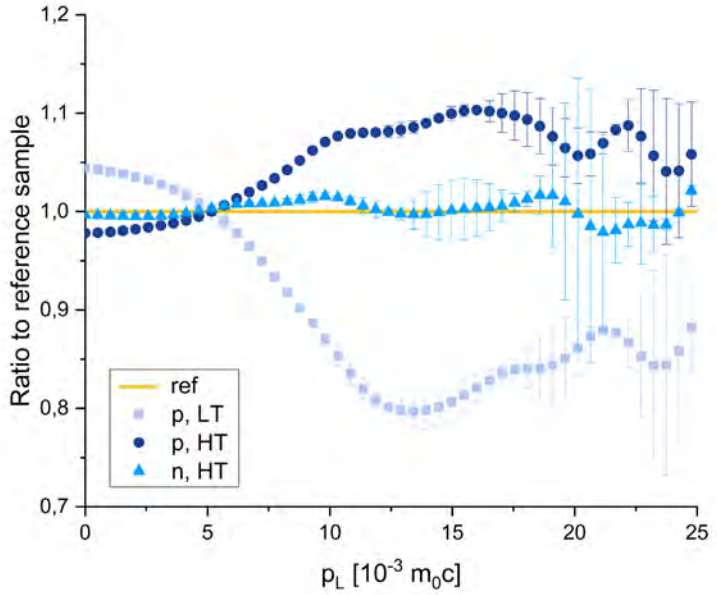


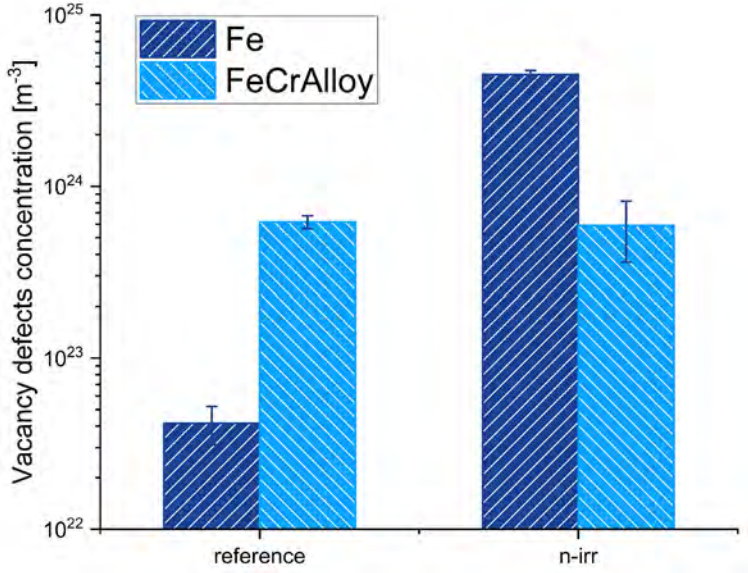
Fig.12,13,14 Vacancy concentration, the CDBS S-W results and momentum curve of FeCrAl alloy before and after irradiation.

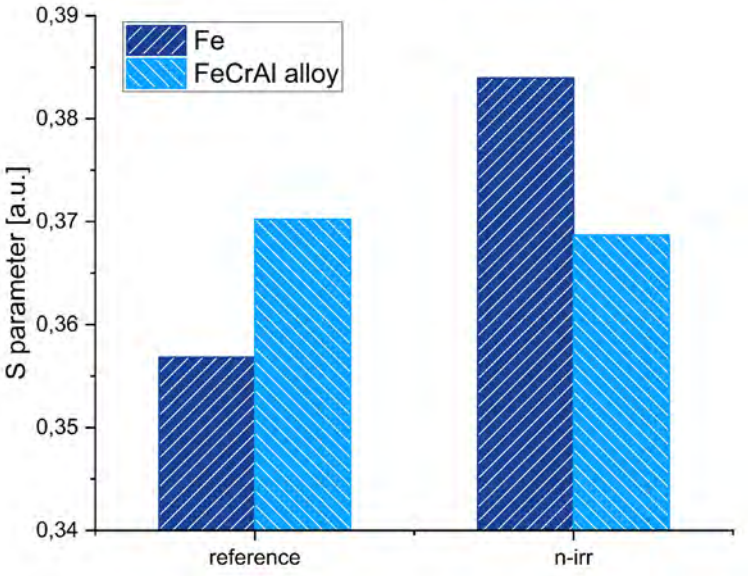
RESULTS

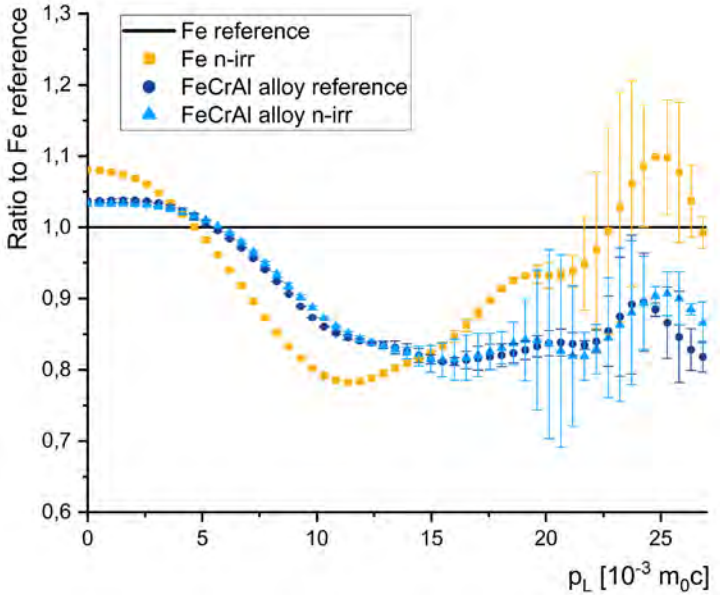
Fe vs. FeCrAl

Presented at

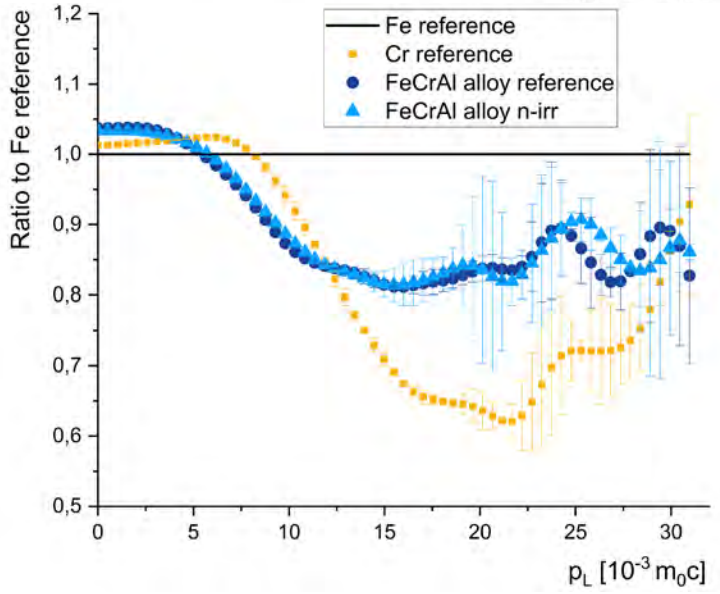
- FeCrAl behaves more stably
- Possibly explained by presence of Cr-rich precipitates (defect sinks)
- Momentum curve analysis suggests presence of Cr precipitates







Fe vs. FeCrAl comparison



FeCrAl vs. pure Cr comparison

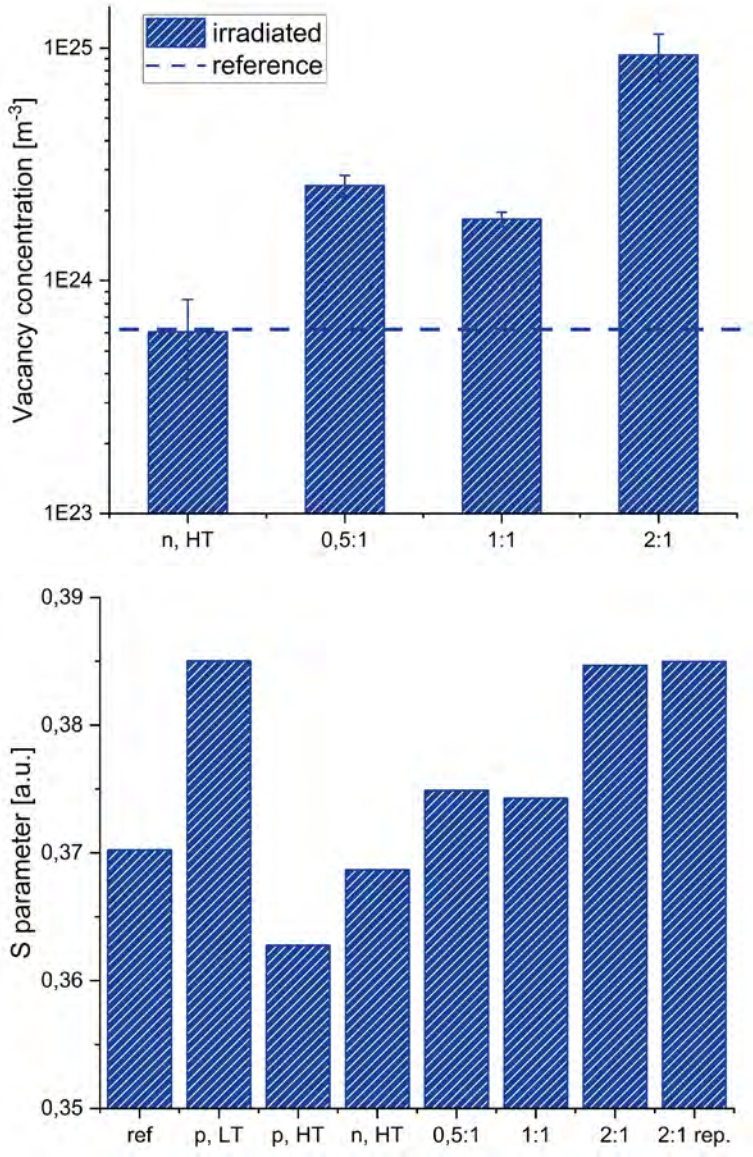
Fig.15,16,17,18 Vacancy concentration, the CDBS S results and momentum curves of FeCrAl alloy before and after irradiation.

RESULTS

Follow-up project RIDER

- n, HT + p, LT experiment
- H fluences designed to follow a hydrogen-to-vacancy ratio
- Study of H-V interaction and H embrittlement

FeCrAl alloy



Tab.5 Hydrogen to vacancy ratio and respective fluences of implanted hydrogen.

H:V	Fluence [cm-2]
0,5:1	1,3E+16
1:1	2,6E+16
2:1	5,1E+16

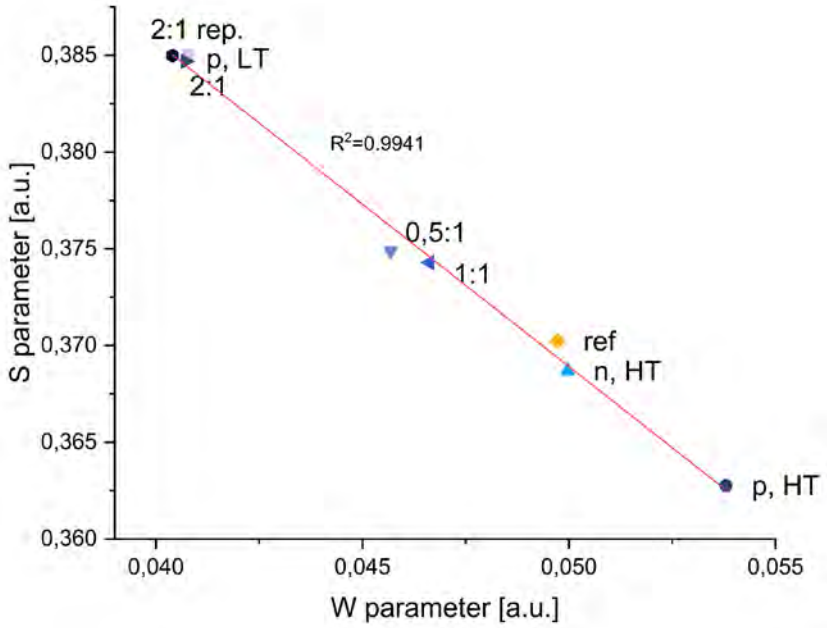


Fig.19,20,21 Vacancy concentration, the CDBS S and S-W results of FeCrAl alloy irradiation and implantation at three different fluences.

CONCLUSION

- Influence of temperature on **recombination** and **presence of hydrogen** in implanted samples
- **Vacancy stabilization** by hydrogen in the case of LT proton implantation
- Possible use of **LT proton implantation to simulate fusion relevant neutrons** in terms of vacancy production in early stages of radiation damage
- **At certain** implantation **fluences** the **vacancy** clusters may be **completely filled with hydrogen**, resulting in **„less damaged“** material (needs further investigation)

THANK YOU

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