

# Influence of High Energy Heavy Ions on Magnetic Susceptibility of Soft Magnetic Metallic Glasses

M. PAVLOVIČ<sup>a,\*</sup>, M. MIGLIERINI<sup>a,b</sup>, E. MUSTAFIN<sup>c</sup>, T. SEIDL<sup>c,d</sup>, M. ŠOKA<sup>e</sup>, W. ENSINGER<sup>d</sup>

<sup>a</sup>Institute of Nuclear and Physical Engineering, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, Ilkovičova 3, 812 19 Bratislava, Slovakia

<sup>b</sup>Regional Centre of Advanced Technologies and Materials, Palacky University, 17. listopadu 12, 771 46 Olomouc, Czech Republic

<sup>c</sup>GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, 642 91 Darmstadt, Germany

<sup>d</sup>Darmstadt University of Technology, Karolinenplatz 5, 642 89 Darmstadt, Germany

<sup>e</sup>Institute of Electrical Engineering, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, Ilkovičova 3, 812 19 Bratislava, Slovakia

This contribution presents experimental data concerning the influence of fast heavy ions on magnetic susceptibility of VITROVAC<sup>®</sup>6025 and VITROPERM<sup>®</sup>800 metallic glasses. Samples of magnetic ribbons were irradiated with Au, and Ta ions at 11.1 MeV/A (energy per nucleon), and U ions at 5.9 MeV/A. The irradiation fluences varied from  $5 \times 10^{10}$  up to  $1.2 \times 10^{13}$  ions/cm<sup>2</sup>. Relative change of the samples' magnetic susceptibility after and before irradiation was measured and evaluated as a function of the irradiation fluence. Measurements were done with a commercial Kappa-bridge device. We observed that VITROPERM<sup>®</sup> showed less change of magnetic susceptibility in comparison with VITROVAC<sup>®</sup> and this change occurred at higher fluences. This indicates higher radiation hardness of VITROPERM<sup>®</sup> compared with VITROVAC<sup>®</sup> against high-energy heavy ions. In addition, heavier ions caused larger change of magnetic susceptibility than the lighter ones and the effect could be roughly scaled with the level of electronic stopping.

DOI: [10.12693/APhysPolA.126.54](https://doi.org/10.12693/APhysPolA.126.54)

PACS: 61.80.Jh, 61.82.Bg, 75.30.Cr, 75.47.Np, 75.50.Kj

## 1. Introduction

Soft-magnetic metallic glasses are considered for magnetic cores of accelerator radio-frequency (RF) cavities. In this particular application, they are exposed to ion irradiation, which alters their magnetic properties. The radiation field is rather complex (different particles, energies and fluences) because it originates from interaction of lost primary heavy ions with the beam-pipe producing different secondary particles. That is why a systematic study of the influence of ion irradiation on magnetic properties of the soft-magnetic metallic glasses is important. Our study is connected to the FAIR project [1]. Having some experience with neutron- and laser-irradiation of different metallic glasses [2, 3], we started with light ions [4, 5]. However, the data for light ions cannot be extrapolated to heavy ions, because the mechanism of radiation damage is qualitatively different for light vs. heavy ions [6]. The recent work covers Ta, Au and U ions irradiating ribbons of VITROVAC<sup>®</sup>6025 and VITROPERM<sup>®</sup>800 [7] at energies of few MeV/A (per nucleon). After irradiation, the samples showed changes of magnetic susceptibility. These changes were a function of irradiation fluence, ion mass as well as sample material.

## 2. Materials and methods

All irradiation experiments were performed at the UNILAC accelerator at GSI Helmholtzzentrum für Schwerionenforschung. The irradiation conditions are given in Table I.

A summary of irradiation conditions, TABLE I

Material	Ion, energy [MeV/A]	Fluence [ions/cm <sup>2</sup> ]
VITROVAC <sup>®</sup>	Au, 11.1	$5 \times 10^{10}$ , $1 \times 10^{11}$ , $5 \times 10^{11}$ $1 \times 10^{12}$ , $3 \times 10^{12}$
	Ta, 11.1	$1 \times 10^{11}$ , $5 \times 10^{11}$ , $1 \times 10^{12}$ $2 \times 10^{12}$ , $5 \times 10^{12}$ , $1.2 \times 10^{13}$
VITROPERM <sup>®</sup>	Au, 11.1	$1 \times 10^{11}$ , $5 \times 10^{11}$ , $1 \times 10^{12}$ $2 \times 10^{12}$ , $5 \times 10^{12}$
	U, 5.9	$1 \times 10^{11}$ , $5 \times 10^{11}$ , $1 \times 10^{12}$ $2 \times 10^{12}$ , $5 \times 10^{12}$

Prior to each irradiation, simulations with SRIM2010 were run in the full-cascade mode in order to evaluate ionization density and radiation damage. Ionization density corresponds to electronic stopping. Radiation damage was converted to dpa (displacements pre atom) and corresponds to elastic nuclear scattering. Figure 1 shows ionization density and dpa for VITROPERM<sup>®</sup>800. Data for VITROVAC<sup>®</sup>6025 can be found in [8]. In all cases, the range of ions is longer than the sample thickness, that is about 23  $\mu\text{m}$ .

\*corresponding author; e-mail: [marius.pavlovic@stuba.sk](mailto:marius.pavlovic@stuba.sk)

The samples were analysed by magnetic susceptibility measurements, using the commercial Kappa-bridge KLY-2 system [9]. Its operation is based on measurement of inductance-change of a pick-up coil due to presence of a magnetic specimen in its centre. The pick-up coil is a 6th-order compensated solenoid. The electric circuit is an accurate auto-balance inductivity bridge. The operating frequency is 920 Hz. The absolute accuracy declared by the manufacturer is  $\pm 3\%$ . Each set of samples contained one reference sample that was not irradiated and served for fine calibration. With this calibration, we estimate the accuracy of the presented data better than  $\pm 1.5\%$ .

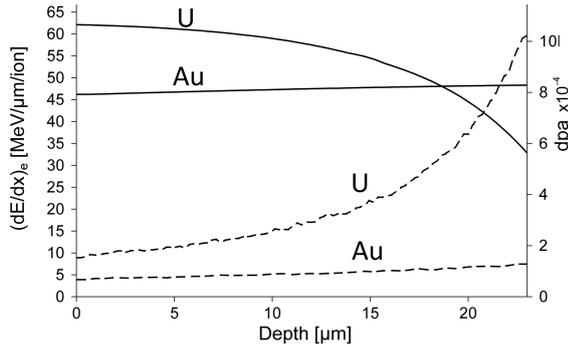


Fig. 1. Ionization density ( $dE/dx$ , solid line, left scale) and radiation damage (dpa, dashed line, right scale) for Au and U ions in VITROPERM<sup>®</sup>800 simulated with SRIM2010 at irradiation fluence of  $1 \times 10^{12}$  ions/cm<sup>2</sup>.

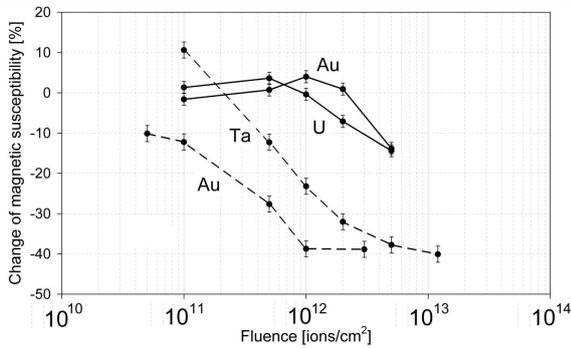


Fig. 2. Relative change of magnetic susceptibility induced by fast heavy ion irradiation as a function of irradiation fluence. VITROVAC<sup>®</sup>6025 – dashed line, VITROPERM<sup>®</sup>800 – solid line.

### 3. Results, discussion and conclusions

Figure 2 shows the measurement results in form of the relative change of magnetic susceptibility induced by ion irradiation as a function of irradiation fluence.

It is observed that: (1) the relative change of magnetic susceptibility is larger for VITROVAC<sup>®</sup>6025 in comparison with VITROPERM<sup>®</sup>800 and (2) the radiation damage caused by heavier ions is greater than the damage

caused by lighter ions (see Tab. II for selected numerical data).

One can state as a conclusion that VITROPERM<sup>®</sup>-type materials are radiation harder compared with VITROVAC<sup>®</sup>-type materials against high energy heavy ion irradiation.

TABLE II  
Relative change of magnetic susceptibility [%].

Fluence [ions/cm <sup>2</sup> ]	VITROVAC <sup>®</sup>		VITROPERM <sup>®</sup>	
	Ta	Au	Au	U
$1 \times 10^{11}$	11	-12	-2	1
$5 \times 10^{11}$	-12	-28	1	4
$1 \times 10^{12}$	-23	-39	4	0
$2 \times 10^{12}$	-32		1	-7
$5 \times 10^{12}$	-38	-39*	-14	-14

\*Data-point at irradiation fluence  $3 \times 10^{12}$  ions/cm<sup>2</sup>.

### Acknowledgments

This work was supported through the VEGA projects 1/0286/12 and 1/1163/12. Further support was provided by the Slovak Research and Development Agency (contract Nos. APVV-0062-11 and SK-PL-0032-12). Support from TU Darmstadt, BMBF 06DA90251, GSI Helmholtzzentrum für Schwerionenforschung GmbH, CZ.1.07/2.3.00/20.0155, and CZ.1.05/2.1.00/03.0058 is acknowledged as well.

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