INFLUENCE OF XENON ION IRRADIATION ON MAGNETIC SUSCEPTIBILITY OF SOFT-MAGNETIC METALLIC ALLOYS

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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 caused by the lost beam particles, which may alter their magnetic properties [1]. The spectrum of irradiating particles is rather complex (different particle species, energies and fluences) because they origin from interaction of lost primary heavy ions with the beam-pipe wall 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 necessary.

Previous studies concentrated on light-ions, namely protons and nitrogen ions [2, 3]. Unfortunately, the data obtained for light ions cannot be extrapolated to heavy ions, because the mechanism of radiation damage is qualitatively different for light vs. heavy ions [4]. That is why next studies covered heavy ions, namely tantalum, gold and uranium [5]. This paper presents the results of magnetic susceptibility measurements of VITROPERM® [6] irradiated with Xenon ions at 11.1 MeV/u representing an intermediate mass of irradiating particles.

2. Experimental Details

VITROPERM®800 ($Fe_{73}Cu_1Nb_3Si_{16}B_7$) was irradiated by Xe ions at 11.1 MeV/u using the UNILAC accelerator at GSI Darmstadt. At this energy, the range is longer than the sample thickness (≈ 23 μm) and ions pass through the sample. Radiation damage profile and ionization (electronic stopping) profile are shown in Figure 1. Radiation damage is expressed in displacements per atom, dpa and is related to elastic nuclear scattering. Simulations were performed with SRIM2010 in the full-cascade damage mode. Applied fluences are listed in Table 1. There were two irradiation campaigns applied to the sample set. After the first beam-time, the magnetic susceptibility was measured twice with approximately 6 months break in-between. After that, the samples were irradiated once again in order to obtain complementary data-points as well as to get higher irradiation fluences by cumulating two partial fluences. After the second irradiation, the magnetic susceptibility was measured twice again. The first and the second irradiation campaign were separated approximately by 12 months.

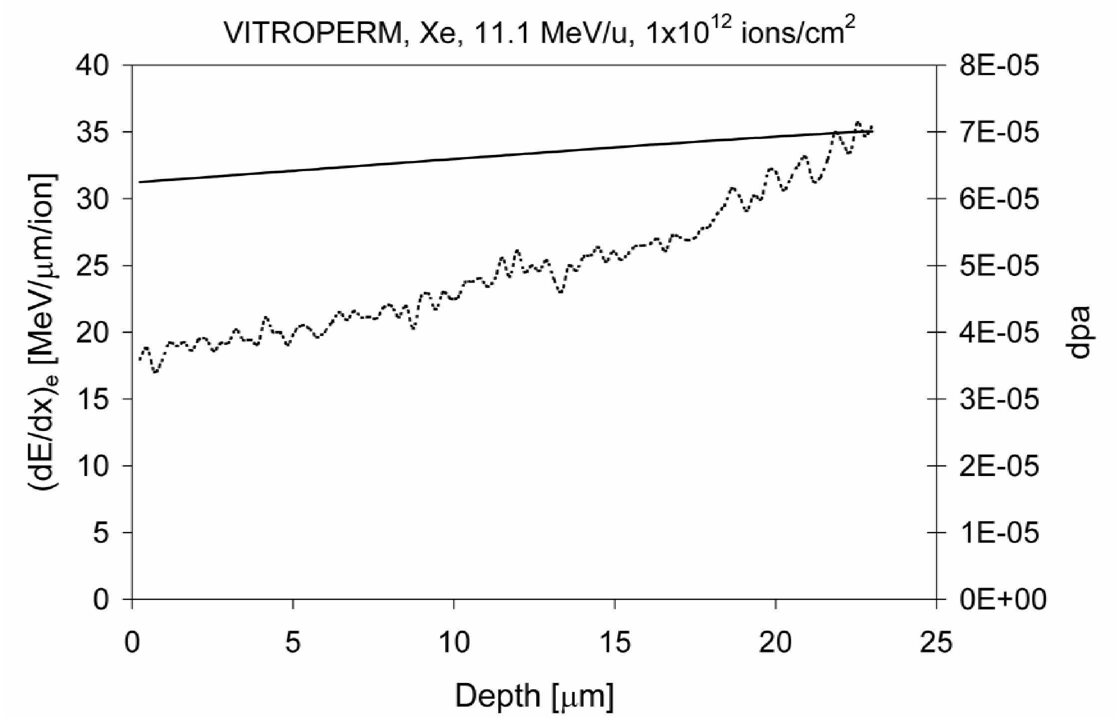

Fig.1: *Ionization (solid-line, left scale) and radiation damage (dotted-line, right scale) in VITROPERM irradiated by 1×10^{12} Xe ions/cm^2 at 11.1 MeV/u as calculated with SRIM2010. Radiation damage is expressed in dpa = displacements per atom.*

Tab. 1. *Irradiation conditions for VITROPERM at 11.1 MeV/u.*

Irradiation campaign number	Specimen identification	Fluence [ions/cm^2]	
		Irradiation	Cumulative
1	A	1×10^{11}	1×10^{11}
1	B	5×10^{11}	5×10^{11}
1	C	1×10^{12}	1×10^{12}
1	D	2×10^{12}	2×10^{12}
1	E	5×10^{12}	5×10^{12}
2	A	5×10^{12}	5.1×10^{12}
2	B	2×10^{12}	2.5×10^{12}
2	C	5×10^{12}	6×10^{12}
2	D	2×10^{12}	4×10^{12}
2	E	5×10^{12}	1×10^{13}

3. Magnetic susceptibility measurements

The samples were analysed by magnetic susceptibility measurements using Kappa-bridge KLY – 2 [7]. It is a commercial system for magnetic susceptibility measurements. Its operation is based on measurements of inductivity change of a pick-up coil due to presence of a magnetic specimen in its centre. In principle, it is an accurate auto-balance inductivity bridge. The pick-up coil is designed as a 6^{th}-order compensated solenoid with highly homogeneous magnetic field. Some main specifications as declared by the manufacturer are listed in Table 2. It should be noted that the operating frequency of the Kappa-bridge is 920 Hz, whereas the working range of accelerator RF cavities can be significantly higher.

Tab. 2. *Main specifications of the Kappa-bridge KLY – 2.*

Inner diameter of the pick-up coil	43 mm
Magnetic field intensity (r.m.s.)	300 A/m
Field homogeneity	0.2%
Operating frequency	920 Hz
Accuracy within one range	± 0.1%
Accuracy of the range divider	± 0.3%
Accuracy of absolute calibration	± 3%

The samples were measured at 304 K and 307 K and the average value from these two measurements was taken as a data-point. In order to increase accuracy, the set of samples contained one reference sample that was not irradiated. It served for consistency checks of data taken at each measurement. This was necessary because of relatively long time-break (about 6 months) between individual measurements, which was related to the beam-time availability cycle. The difference in measured values for the reference sample stayed within the ± 3% indeed, as declared by the manufacturer. The data of irradiated samples were corrected (shifted) using the shift measured for the reference sample. That is why we can assume that the presented data are measured with accuracy better than ± 3%. Repeated measurements (after this correction) stayed within ± 1.5% even for different samples "meeting" at the same or similar cumulative fluence.

4. Results, discussion and conclusions

Relative change of magnetic susceptibility as a function of irradiation fluence is shown in Figure 2.

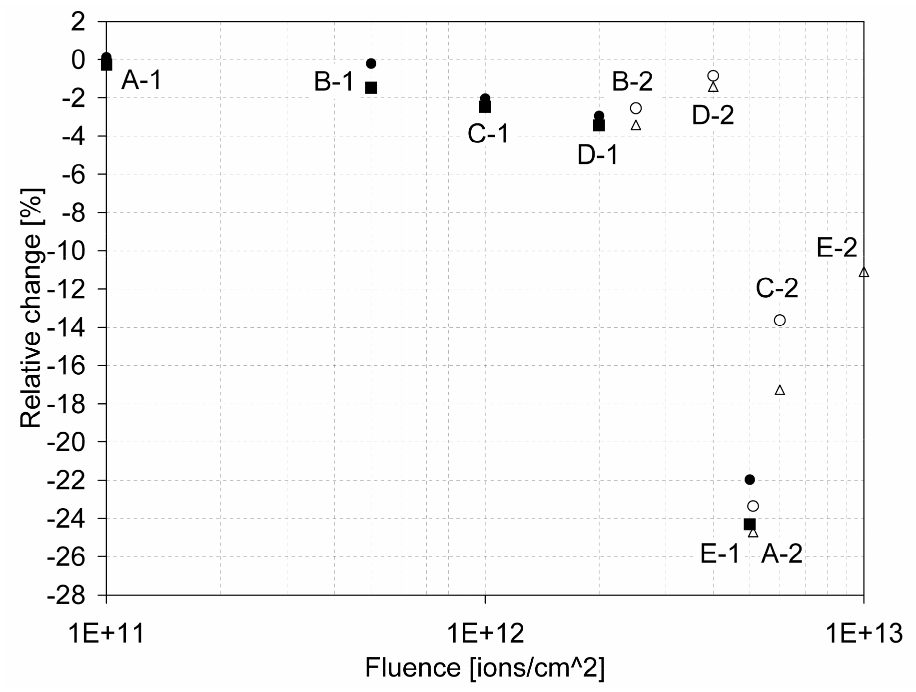

Fig.2: *Relative change of magnetic susceptibility as a function of irradiation fluence. Dark symbols=after the 1st irradiation, open symbols=after the 2nd irradiation.*

The sample-coding is the following: the letter indentifies the sample, whereas the number identifies the irradiation campaign. The dark symbols refer to the two measurements after the 1st irradiation, whereas the open symbols refer to the two measurements after the 2nd irradiation. It can be seen that the drop of magnetic susceptibility stays below – 4% up to the fluence of 4×10^{12} Xe ions/cm^2. At 5×10^{12} Xe ions/cm^2, it drops suddenly to – 24%. One can conclude that VITROPERM is radiation-hard till the fluence of about 4×10^{12} Xe ions/cm^2. Because the data-points B-2 and D-2 represent a cumulative dose, the radiation-hardness threshold can be related to the cumulative dose.

An interesting discussion can be made about the consistency of the measured data. Figure 2 illustrates clearly that the data are consistent up the fluence 5×10^{12} Xe ions/cm^2. Especially the four data-points at this particular fluence are representing two different samples irradiated in two different modes. Sample E-1 received 5×10^{12} Xe ions/cm^2 in one beam-time, whereas sample A-2 received 5.1×10^{12} Xe ions/cm^2 as a superposition of 1×10^{11} Xe ions/cm^2 in the 1st beam-time and 5×10^{12} Xe ions/cm^2 in the second one. Despite of these different conditions, the drop of the magnetic susceptibility is almost the same (within ± 1.5%). This is no longer true for the samples having received higher fluence. The two C-2 measurements are less consistent and the second measurement of the E-2 sample was even out of scale of the plot. This suggests some enhanced aging effects at samples irradiated by high fluence of heavy ions.

The radiation damage due to the elastic nuclear scattering is very low (dpa $\leq 1\times10^{-4}$). This suggests that the main mechanism of radiation damaging for heavy ions is related to the electronic stopping and the ionisation density. This quantity should be a suitable parameter to scale / compare / predict radiation damage of materials caused by swift heavy ions [5]. That is why future irradiation experiments are planned with electron beams at the University Centre of Electron Accelerators, Slovak Medical University.

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