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Materials irradiation facilities at the high-power Swiss proton accelerator complex

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Abstract

Within the Swiss proton accelerator complex at the Paul-Scherrer-Institute (PSI), several irradiation facilities are operated for investigation of materials behavior under high-dose irradiation conditions as well as for neutron activation analysis and isotope production. In LiSoR (liquid solid reaction), a liquid metal loop connected to the 72 MeV proton accelerator Injector 1, steel samples are irradiated while being in contact with flowing lead–bismuth-eutectic (LBE) at elevated temperatures and under tensile stress. In the spallation neutron source SINQ, the STIP program (SINQ Target Irradiation Program) allows materials irradiation under realistic spallation conditions, i.e. in a mixed spectrum of 570 MeV protons and spallation neutrons. Hundreds of samples, mainly austenitic and ferritic–martensitic steels such as 316L, T91 or F82H, were irradiated to doses up to 20 dpa as part of STIP. These also included steel samples in contact with liquid Hg and liquid LBE. MEGAPIE (MEGAwatt PIlot Experiment), a liquid metal target employing LBE, operated in SINQ during the second half of 2006, can be taken as a materials irradiation facility on its own. Adjacent to the target position, SINQ houses a neutron irradiation rabbit system serving activation analysis and isotope production.

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1. Introduction

Despite decades of experience in reactor technology and accelerator developments, materials in high-dose irradiation environments are still an issue of widespread interest. Related to that, there is worldwide an increasing demand for appropriate materials irradiation facilities. The demand stems from different disciplines: Target development initiatives for spallation neutron sources or neutrino factories, new fission reactor lines (Generation IV) and also fusion reactor technology. Their common requirements are to accumulate a meaningful dose, i.e. a sufficient number of dpa's (displacement per atom) during a tolerable irradiation period, from a correct spectrum of irradiating particles and at the correct temperatures of interest. The latter two requirements are partly diverging from case to case: whereas spallation sources have to deal typically with a mixed spectrum of protons and neutrons, the new fission reactor lines require a spectrum of mainly fast neutrons with no protons, and the fusion technology is heading for a 14 MeV neutron spectrum. The temperature requirements range

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from just above room temperature (spallation sources) to high temperatures up to and above 1000 °C (Generation IV).

In addition to a relatively limited number of operating and accessible irradiation facilities, three dedicated large irradiation facilities are presently under consideration or in the project planning phase: The Los Alamos Material Test Station (MTS) that projects a 1 mA/800 MeV proton beam spallation target in a sandwich structure with the irradiation specimens placed in the centre in a spectrum of primarily fast neutrons (goal: 10^{15} n/cm^2/s); IFMIF (International Fusion Materials Irradiation Facility) that is dedicated for fusion reactor materials irradiation [1]; the Jules-Horowitz (JH) reactor project [2]. For all three, the final decisions for funding and the dates of realization are still open. MTS has a chance to start in 2008. For IFMIF and JH the estimated budget requirements are between 500 and 1000 M€, and, if funded, the earliest completion date is after 2015. On a short or intermediate time frame this scenario is not at all very encouraging.

PSI operates a proton accelerator complex, combining a 72 MeV injector and 590 MeV ring cyclotron with a final beam power in the MW range: a 1.8–2 mA proton beam is routine at present, and upgrades to ultimately 3 mA are planned. The first two targets in the proton beam line are graphite targets for meson (muon and pion) production, followed by the final heavy metal target used for the spallation neutron source SINQ [3]. The time structure (51 MHz) of the proton beam is lost after hitting the spallation target, thus, SINQ is effectively a continuous spallation source at the MW beam power level.

The PSI accelerator complex, including SINQ, offers various options for materials irradiation to high doses in proton and/or neutron beam environments. The stations currently in use are the followings: (i) The LiSoR (liquid solid reaction) facility at the (old) Injector 1 beamline position, which receives a 72 MeV proton (or on demand He or heavier ions) beam of small (mm) size and max 50 μA/cm^2 of beam current density, (ii) STIP, the SINQ Target Irradiation Program, where the SINQ target sample rods in the central reaction zone are used to irradiate material specimens by a mixed spectrum of 570 MeV protons and spallation neutrons, (iii) a neutron irradiation rabbit system, transporting sample capsules to positions inside the D_2O moderator vessel in close vicinity of the spallation target. MEGAPIE (MEGAwatt Pilot Experiment), a liquid metal target employing lead–bismuth-eutectic (LBE), operated in the second half of 2006, may be considered as an irradiation facility on its own. In particular, the beam window deserves paramount attention: Fabricated of ferritic–martensitic steel T91 (9Cr2WTaV), it received the full load of a MW scale proton beam in contact with an inner circulating liquid LBE.

The present paper aims to compile specific details on these irradiation facilities, and elucidate their potentials (and limitations) in view of materials irradiation needs of the interested communities.

2. LiSoR

As mentioned in the introduction MEGAPIE used LBE as the spallation material and the ferritic–martensitic steel T91 as the beam entrance window. LiSoR was launched as a supporting R&D facility for MEGAPIE to investigate the simultaneous influence of flowing LBE at elevated temperatures, mechanical stress and irradiating protons on steel T91 to gain predictive information on the behavior of the steel under MEGAPIE relevant conditions.

LiSoR is an experimental LBE loop equipped with an electromagnetic pump, a flow meter and a heat exchanger system. Details of the LiSoR loop can be found in previous reports [4,5]. It has an exchangeable test section housing the test specimen, the whole loop being designed and constructed for operating in the environment of a proton beam bunker. Fig. 1 shows a photograph of a LiSoR test specimen, the dimensions in the proton beam area being 20 mm in width and 1 mm in thickness. A sketch of the test section is given in Fig. 2 showing the test tube (which houses the test specimen), the LBE in- and outlet, and the grip for the stress actuator. A real test tube, after having been irradiated and dismantled, is shown in Fig. 3. The photo was taken in the hot cell; the beam footprint is clearly visible at the lower half of the central test tube. It illustrates that, in addition to the test specimen on the inside, the test tube itself becomes an irradiation sample, the inside being in contact with liquid LBE and the outside in vacuum. Both samples were always examined. In addition, unirradiated reference material was available which was not in the proton beam but otherwise has experienced the same load and environment.

Although the beam energy of 72 MeV is considerably lower than that of MEGAPIE (570 MeV),