FEASIBILITY STUDY OF NEW MICROSCOPIC FISSION CHAMBERS DEDICATED FOR ADS

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Abstract

In the frame of the MEGAPIE project we propose to measure the neutron flux inside the molten 1 MW Pb-Bi target at PSI (Switzerland). For this purpose a new type of microscopic fission chambers, developed for on-line measurements of the actinide incineration rates in the high neutron fluxes, will be placed in the central rod of the Pb-Bi target to determine both thermal and fast components of the neutron spectra. In addition to the neutron flux measurements in absolute value, both – time and space-dependent variations – of it will be monitored on-line with a precision better than 10%. In this work we show that these measurements are feasible.

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Introduction

In the frame of the MEGAPIE (from **MEGA**watt **PI**lot **E**xperiment) project, [1] a Pb-Bi liquid target will be installed at the SINQ spallation neutron source [2] of the Paul Scherrer Institut (Switzerland). It will assess experimentally the performance of a 1 MW liquid target during 6-9 month irradiation period. This will be an essential step for the further development of high power molten targets in the 20-50 MW range required for Accelerator-driven systems (ADS) such as high intensity spallation neutron sources, hybrid reactors, RNB production or neutrino factories, etc. It is clear that for this type of, so-called, new generation facilities an adequate detection system has to be developed.

In this respect, in order to measure on-line the incineration rate of minor actinides in high neutron fluxes, we have developed innovative microscopic Fission Chambers (μFCs) working in a current mode. [3,4,7] We note that these μFCs have been successfully tested in the High Flux Reactor at the Institut Laue Langevin (ILL) in Grenoble (France). Although these detectors have been initially developed for transmutation rate measurements, in principle, the same μFCs can be used for on-line flux monitoring. [4,7]

Encouraged by the first experimental results, in this work we present a feasibility study of the μFCs as above to use for the accelerator-driven systems (ADS). The European MEGAPIE project [1] was taken as an example of a potential neutron source able to host our newly developed μFCs both for neutron flux as well as for nuclear waste incineration rate measurements in a variable high intensity neutron fluxes. A detailed evaluation how these detectors could function in the typical MEGAPIE neutron and gamma flux environment including particular thermal conditions will be presented in this paper. We believe that our findings could be easily generalised for other ADS projects, where neutron flux levels of about 10^{14}-10^{15} n/(s·cm^2) are expected.

Microscopic fission chambers (μFCs)

In brief, the μFC is a typical gas detector, where the filling gas (Ar) is ionised by fission fragments as a result of the neutron induced fission in a deposit material (see Figure 1 for details). A saturation current, proportional to the fission rate, is determined simply by changing an operating voltage of the chamber. In principle, with these detectors both transmutation rate by fission (incineration) as well as neutron fluxes can be measured on-line. We should note separately that specific experimental conditions, namely neutron fluxes of the order of 10^{15} n/(s·cm^2) or higher, have required substantial modifications of the existing chambers. [1,2]

After the theoretical work, technical design and manufacture has been completed (see Figure 2), these new type of fission chambers were successfully tested in the High Flux Reactor of ILL Grenoble (France). The irradiation took place for ~26 days in a thermal-epithermal neutron flux of the order of 10^{15} n/(s·cm^2), thanks to a newly installed V4 experimental channel. The neutron flux and burn-up rate of the reference material could be observed on-line during the reactor cycle. At the same time a set of conventional flux monitors (Co and Nb samples) have been irradiated in order to cross-check the flux measurements. The data analysis on these irradiated samples is still in progress. [4]

Figure 1. **A simplified view of a cylindrical microscopic fission chamber with ^{235}U deposit** (typically a few tens of µg)

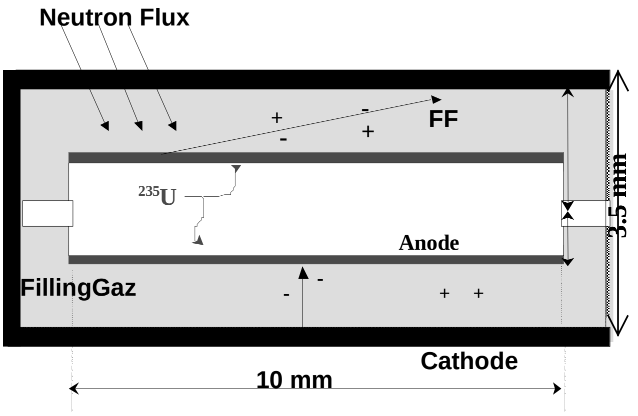
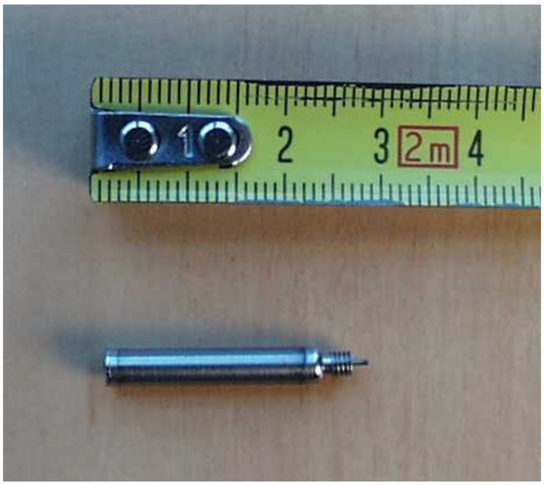


Figure 2. **Photograph of a manufactured microscopic fission chamber** (before connecting with a coaxial mineral insulator cable)



The outstanding performances obtained for our new fission chambers in a very intense neutron flux have validated a new method to determine the transmutation potential of minor actinides (see Figure 3). The intensity of the flux has also been measured with the µFCs giving a value of $1.8 \cdot 10^{15}$ n/(s·cm^2) with a relative uncertainty of 4%. This measurement is in a very good agreement with Monte Carlo predictions reported in [5]. We should stress that it is the first time that a µFC successfully operated in such a high neutron flux, with a gain of more than one order of magnitude on the typical operating flux levels, say, a few 10^{13} n/(s·cm^2).

Applicability of the µFC for ADS

Very promising results on the neutron flux measurements at ILL-Grenoble have encouraged us to propose a unique solution to measure on-line the neutron flux in the high power Pb-Bi liquid target of MEGAPIE. Due to a limited space available in the central rod of the target (~10 mm internal diameter) as shown in Figure 4, microscopic detectors of the same type as we tested in the HFR of ILL-Grenoble (only ~4 mm diameter) are certainly good candidates. To our knowledge, in the present configuration, there is no other alternative way to obtain the required information on the neutron flux on-line inside the Pb-Bi target.

Figure 3. **Experimentally determined burn-up curve using the µFCs (with ^{235}U as a deposit) irradiated at the lowest position of V4 experimental tube at ILL Grenoble**
(note the logaritmic scale and see text for details)

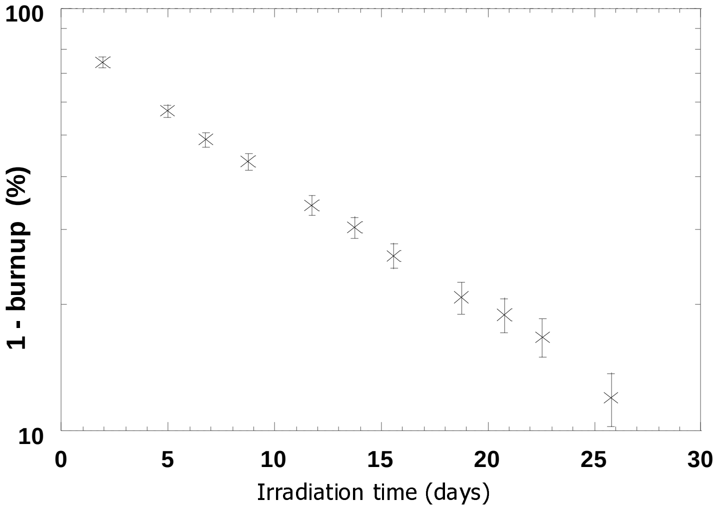
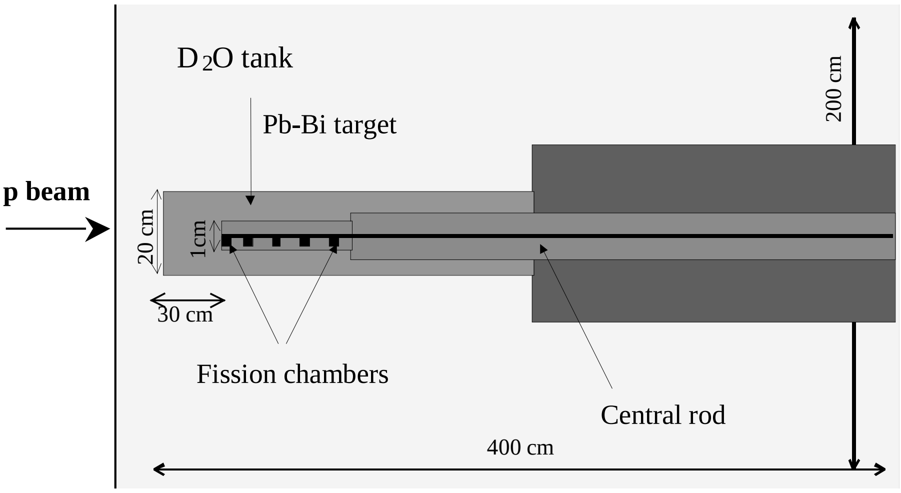


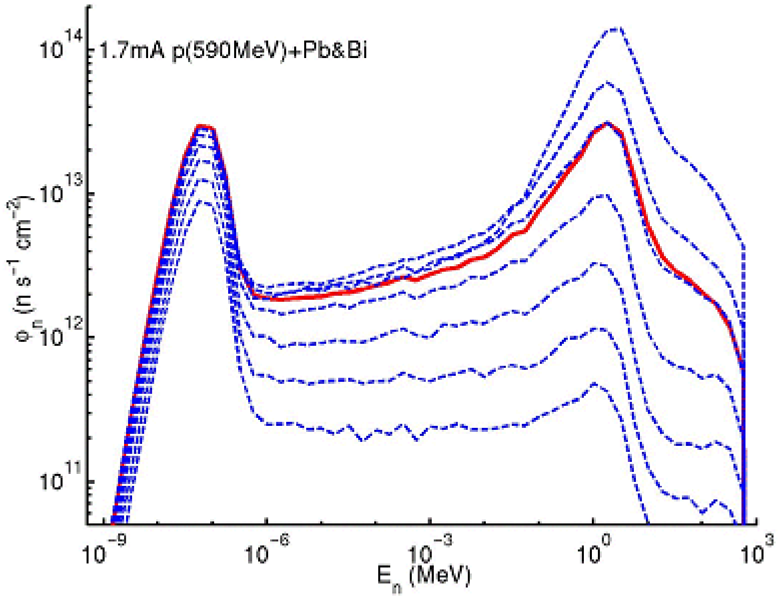
Figure 4. **Scheme of a proposed positioning of the fission chambers in the MEGAPIE target** (not scaled proportionally)



For our investigations a realistic 3D MEGAPIE target geometry was modelled and detailed multi-particle transport simulations were performed using the MCNPX code. [6] In Figure 5 the neutron flux as a function of the neutron energy is plotted for different distances from the beginning of the spallation target. Due to the presence of the D_2O reflector around the Pb-Bi target, a resulting neutron spectrum inside the Pb-Bi target volume contains ~32% of thermal neutrons. As a matter of fact, contribution of thermal neutrons may vary from ~10% to ~85% respectively along the target axis. Solid red curve in the same Figure 5 corresponds to the average neutron flux all over the Pb-Bi target (100 cm long). As it is seen from the comparison of red and blue curves, it is desirable to measure the neutron flux at the distance around 25 cm from the target window, since at this position the neutron flux seems to be the most representative (according to our simulations) if compared to the entire system. Unfortunately, 25 cm thick Pb-Bi is not sufficient to stop all incident protons of 590 MeV

(Brag's peak is located at ~27 cm). In addition, closer to the target window the photon to neutron flux ratio is increasing as presented in Figure 6. Since both proton and photon fluxes could perturb a normal operation of the µFCs, the distance of ~30 cm from the target window was chosen as the closest possible position of our detectors with respect to the target window. In this region neutrons will dominate over gammas by a factor of ~15 (to be compared to the V4 measurements at ILL-Grenoble, where gammas dominated over neutrons by a factor of 2). In addition, at 30 cm proton flux can be fully neglected (see Figure 6 for details). Finally, a µFC without deposit will be placed together with "active" chambers in order to measure the background generated by photo ionisation effects (e.g. photoelectric, pair creation-annihilation, etc.) from gammas and hadrons interacting with the gas, structural materials, and cables of the fission chambers. In this way a current due to the background could be determined without any ambiguity.

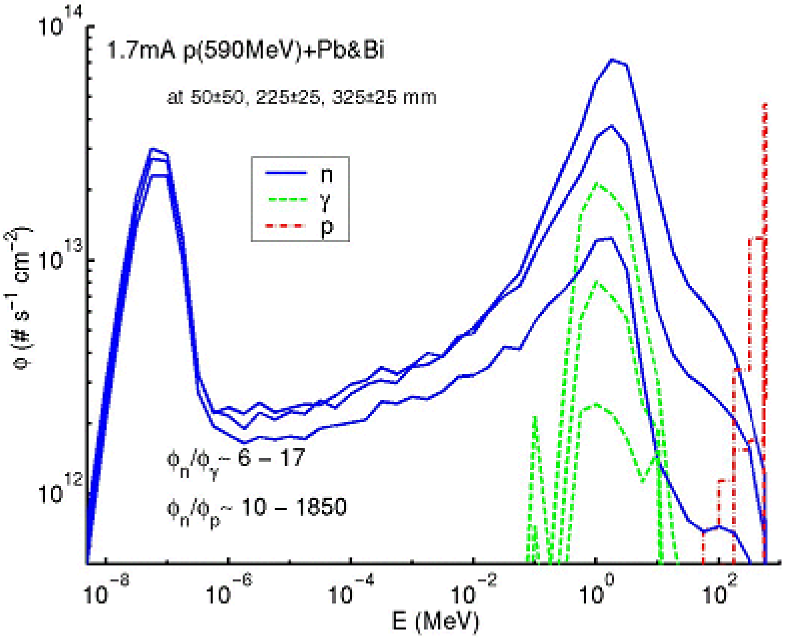
Figure 5. **Volumetric neutron fluxes***



* inside the Pb-Bi target at 5, 15, 25, 35, 45, 55, 65 cm (blue dashed curves from top to bottom) with respect to the very bottom position (beam interaction with window). Red curve presents an average neutron flux over the entire volume of Pb-Bi.

As long as the expected absolute value of the flux is concerned, Monte Carlo simulations with MCNPX show that at the distance of 35 cm from the Pb-Bi target entrance the neutron flux is ~1.7x10^{14} n/(s·cm^2) with ~42% thermal. As a matter of fact, this flux is of the same order of magnitude as the flux measured at the upper position of the V4 beam tube at ILL-Grenoble, i.e. of the order of ~10^{14} n/(s·cm^2). Therefore, we can easily predict an expected saturation current for a given mass and isotopic composition of the actinide deposited on the anode. Table 1 summarises these values for a number of particular cases.

Figure 6. **Comparison of neutron (solid-blue), gamma (dashed-green) and proton (dashed-dotted-red) fluxes inside the Pb-Bi target at different positions** (from top-to-bottom) along the beam axis (also see the legend)



* Proton fluxes at the last position (~32.5 cm) are not seen on this graph being negligible.

The expected saturation current in these fission chambers should be of the same order of magnitude as for the irradiation at ILL-Grenoble, i.e. ~40 μA for ^{235}U and ^{239}Pu deposits. Unfortunately, such materials as ^{232}Th and ^{238}U cannot be used as deposits due to very small expected saturation currents (see Table 1), although they could provide some valuable information on the fast component of the neutron flux.

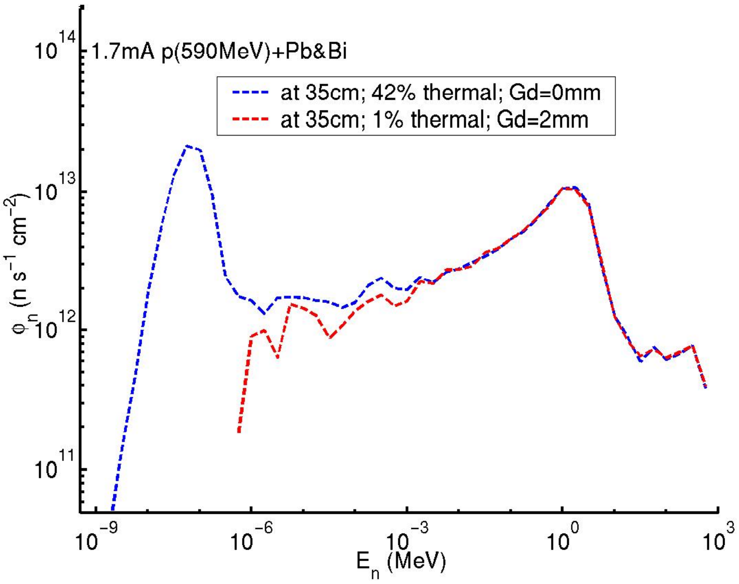
Table 1. **Expected saturation current (I_S) in the fission micro-chambers during irradiation in MEGAPIE for different fissile deposits (all for 20 μg) compared to the current measured during ILL irradiation, with or without thermal neutron shielding**

	Without Gd shielding			**With 1 mm Gd shielding**		
	<σ>, b	<σ > · φ, b · n/(s·cm^2)	I_s, μ A	<σ>, b	<σ > · φ, b · n/(s·cm^2)	I_s, μ A
^{235}U (ILL V4^)	**500**	**3.2 10^{16}**	**44**			
^{235}U (MegaPie)	**270**	**2.7 10^{16}**	**37**	**9.4**	**3.4 10^{14}**	**0.5**
^{239}Pu (MegaPie)	404	4.0 10^{16}	55	10.9	4.0 10^{14}	0.6
^{232}Th (MegaPie)	0.01	1.2 10^{12}	<<1	0.03	1.2 10^{12}	<<1
^{238}U (MegaPie)	0.04	4.0 10^{12}	<<1	0.1	3.6 10^{12}	<<1

* Note that a saturation current value for ILL V4^ is given at the highest position of the experimental channel, where the neutron flux is of the order of 6.4 ·1013 n/(s.cm2) (~100% thermal).

For the measurements of the fast and epithermal component of the neutron flux, we propose to install, at the lowest position in the central rod, a fission chamber (with ~200 μg of ^{235}U or ^{239}Pu as a deposit) shielded by a ~1 mm thick Gd cover. Figure 7 presents explicitly the calculated neutron flux seen by the micro-chambers without and with Gd foil. In this case a saturation current of the order of 5 µA is expected, and now the majority (~98%) of the signal is due to the fissions induced by fast-epithermal neutrons as presented in Figure 7. The low value of the measured current (a few µA) will require new acquisition electronic modules with a precision of 10 nA.

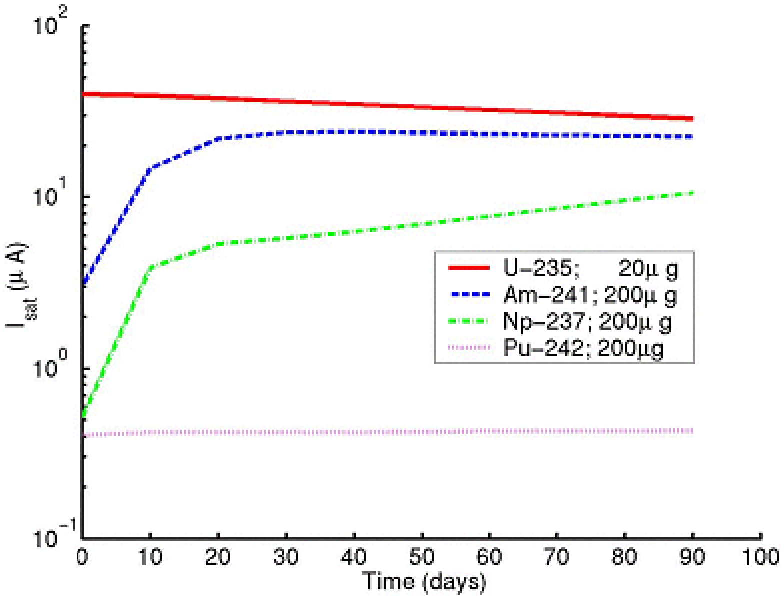
Figure 7. **Neutron flux at 35 cm in Pb-Bi without and with natural Gd envelope**



In Figure 8 the performance of the µFCs are presented as a function of burn-up with other potential deposits, namely isotopes of Pu, Am and Np. For comparison, a burn-up curve of ^{235}U is also plotted on the same Figure. In brief, both ^{241}Am and ^{237}Np are interesting candidates as deposits, and therefore will be tried for our purposes. We note separately, that the saturation currents, if successfully measured in these two particular cases, also could be used to extract the corresponding integral fission cross-sections of ^{242}Am and ^{238}Np which are not well known.

Finally, as presented in Figure 4, the µFCs chambers placed at different distances from the target entrance in the central rod will allow to measure the spatial dependence of the thermal flux along the beam axis. Moreover, due to the much smaller (compared to the bottom position of V4 at ILL Grenoble) burn up of the deposit, namely less than 0.3% per day, these chambers will provide also an on-line monitoring of the time dependence of the integral neutron flux. We estimate that during 9 months of operation nearly 35% of initial ^{235}U mass still will be left. This burn-up rate is low enough to measure on line flux variations due to, for example, the beam intensity-energy variations or beam trips. At the same time, this burn-up rate is high enough to re-calibrate our detectors, if necessary, as it was done during the irradiation at ILL Grenoble (see Figure 3).

Figure 8. **Expected evolution of the saturation current, measured with the μFCs as a function of burn-up and different deposit materials, at 35 cm in the Pb-Bi of MEGAPIE**



Conclusions

The neutron flux measurements we proposed to perform in the MEGAPIE target are of a great interest for the knowledge of the realistic irradiation conditions in the futuristic ADS based applications. We showed that with the newly developed μFCs chambers, adopted accordingly for the particular MEGAPIE target conditions, both thermal and fast components of the neutron flux could be determined experimentally including their time and space variations on-line. These measurements will bring a much better understanding of the macroscopic and, in some sense, microscopic processes involved in high power spallation targets and will provide highly requested quantitative data to test simulation codes, both for neutron generation and transport in realistic geometries. In our opinion this feasibility study could be easily generalised for other ADS projects, where neutron fluxes of the order of 10^{14}-10^{15} n/(s·cm^2) are expected.

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