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Basic concept for an accelerator-driven subcritical system to be used as a long-pulse neutron source for Condensed Matter research

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ABSTRACT

A model for an accelerator-driven subcritical system to be operated as a source of cold neutrons for Condensed Matter research is developed at the conceptual level. Its baseline layout relies upon proven accelerator, spalattion target and fuel array technologies, and consists in a proton accelerator able to deliver some 67.5 mA of proton beam with kinetic energy 0.6 GeV, a pulse length of 2.86 ms, and repetition rate of 14 Hz. The particle beam hits a target of conventional design that is surrounded by a multiplicative core made of fissile/fertile material, composed by a subcritical array of fuel bars made of aluminium Cermet cooled by light water poisoned with boric acid. Relatively low enriched uranium is chosen as fissile material. An optimisation of several parameters is carried out, using as components of the objective function several characteristics pertaining the cold neutron pulse. The results show that the optimal device will deliver up to 80% of the cold neutron flux expected for some of the ongoing projects using a significantly lower proton beam power than that managed in such projects. The total power developed within the core rises up to 22.8 MW, and the criticality range shifts to a final k_{eff} value of around 0.9 after the 50 days cycle.

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1. Introduction

Neutron scattering studies on the Condensed Matter Sciences constitute a unique tool for the investigation of fine details of atomic and spin structure and dynamics. In fact, both the achievable energy resolution, which can attain values of a fraction of μeV and also cover a wide range of times (10^{-7}–10^{-13} s) and length (1–500 Å) scales, and the high sensitivity to magnetic moments, as well as the isotope-dependent scattering length, makes neutron beams unrivalled experimental tools. However, the technique, for some applications, has been shown to be limited by the achievable intensity of current neutron fluxes. In fact, a plot originally due to Brugger [1] which depicts the logarithm of the effective thermal neutron flux given in neutrons-cm^{-2} s^{-1}, versus the year of commissioning of the user-dedicated facilities, shows that neutron fluxes for use in experimental facilities have not witnessed dramatic increases since 1950, with values stuck at figures about 10^{15} fast neutrons-cm^{-2} s^{-1} (full bandwidth).

In contrast, photon sources have experienced an impressive surge in brightness which goes from values for average brightness, as measured in units of photons s^{-1} mrad^{-2} mm^{2} 0.1% bandwidth, of 10^{16} for second generation synchrotron radiation sources, up to values of 10^{22} for operating energy recovery linacs, and up to 10^{22}–10^{25} for x-ray free electron lasers under construction or in operation at present.

Compact, experimental, purpose-built reactors were the workhorses of the technique for the past decades and still provide most of the facilities available to users worldwide. The technique has however reached its limits since in order to reach the 10^{16} neutrons-cm^{-2} flux values, power densities of the order of 10 MW l^{-1} are required. Such a heat dissipation problem exceeds the cooling capabilities of usual coolants such as light or heavy water. In consequence, rather different reactor concepts such as pebble-bed or fast reactors with liquid metal coolant are called for if such power densities are to be reached or exceeded. In fact, the maximum fluxes achievable in a thermal reactor are estimated to be $\approx 3.4 \times 10^{17}$ neutrons-cm^{-2} s^{-1}. Such fluxes, only achievable with a density of fissile nuclei of the order of 10^{17} cm^{-3} do however pose extreme technical requirements and, on the other hand, the lifetime of the fissile material will be unpractically short, all but a few hours.

Accelerator-driven neutron production targets can, in principle, surpass the limitation above referred to. In fact, neutron yield data in terms of neutron multiplicities, $M(E_p)$ per incident proton for beam energies up to 12 GeV can be approximately parametrised [2] by a sublinear relationship given by

$$M(E_p) = M_0 + M_1 E_P^x \quad (1)$$

with parameters corresponding to a thick lead (Pb) target of $M_0 = -8.2 \pm 1.6$, $M_1 = -29.3 \pm 1.3$ and x=0.75. There are however some caveats that largely limit the potential capabilities of the technique. First, the sublinear dependence of Eq. (1) means that although multiplicities as high as about 180 neutrons per incident proton can be achieved with a beam of 12 GeV protons, the costs incurred in building such an accelerator largely offset the benefits of such large neutron yield. In fact, if neutron multiplicities are plotted as multiplicity per MeV of incident proton energy versus proton energy as shown in Fig. 1, which constitutes a simple measure of the efficiency of the neutron generation process; one directly infers that there is not much advantage, costs-wise, in building accelerators delivering beams with energies well in excess of 0.8–1.0 GeV.

On the other hand, whereas there seems to be no obvious limitation for building higher energy and high proton current accelerators, delivering such beams to a neutron production target involves a number of issues which need to be taken care of. First, due consideration needs to be made to the thermal properties of target materials which come close to the known limits for most materials for beam powers of about 3–5 MW. Beams with a power exceeding such figures need to be delivered onto a larger volume of target material in order to decrease the specific power density down to manageable levels. To such an avail, liquid metal or solid, rotating target concepts are the options nowadays into consideration. Finally, but not less important, increasing electricity costs would make the operation ones for higher energy proton accelerators difficult to cope with, which put into other words, it makes mandatory to optimise the neutrons to be generated per megawatt of beam power.

In contrast and with a limited impact on the design of new neutron sources, the 1990s witnessed the development of high power accelerator sources coupled to an array of sub-critical fissile or fertile materials with the purpose of either transmutation of nuclear waste (ATW), production of tritium (APT) or even, accelerator-driven energy production (ADEP). Common to all of these is the requirement of a high power proton or deuteron accelerator operating in continuous wave mode with optimal energies within 0.8–1.0 GeV (minimum cost – performance optimised) and currents from 10 mA needed for ATW or ADEP, to 100 mA for APT and up to 300 mA to breed fissile materials. Spallation targets will either contain a heavy metal (W, Hg, Pb–Bi) or depleted uranium, and will be surrounded by a fuel assembly. Operation with a sub-critical regime is envisaged for multiplication constants with typical values of $k \simeq 0.900$–0.955 (see Appendix Appendix A). The concepts here involved are not new. In fact, the idea of combining a high-intensity accelerator impinging on a neutron production target was first discussed within the realm of transmutation of spent fuel by Steinberg [7], later considered within the Canadian Intense Neutron Generator project [8] and more recently the issue was reappraised by Gokhale [9].

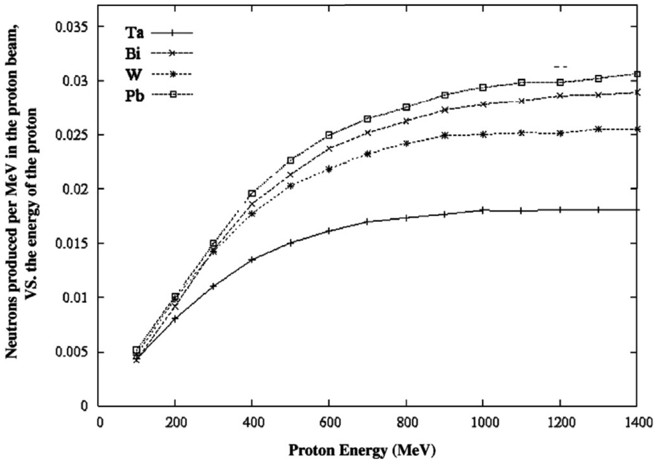

Fig. 1. Neutron produced per MeV of the impining proton beam [3] for selected target materials.