An Intense Pulsed Spallation Neutron Source using a High-Power Proton Linac for Nuclear Transmutation

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Abstract

The construction of a high-power proton linac is being planned by the Japan Atomic Energy Research Institute for the nuclear transmutation of rare actinides in nuclear wastes (Omega Program, Science and Technology Agency, Japan/OECD NEA). The accelerator can also be utilized in basic science. An intense spallation neutron source for condensed-matter science is a typical application. This will provide an opportunity to realize a MW-class pulsed spallation neutron-source. We would propose this as a next-next-generation (post JHP/KENS-II) pulsed spallation neutron source in Japan. We discuss here the possibility of realizing this idea.

1. Introduction

The construction of an intense proton linac, called ETA (Engineering Test Accelerator), has been proposed by the Japan Atomic Energy Research Institute (JAERI) as a part of R&D plans for an accelerator-based rare actinide transmutation system.(1) The specifications of ETA are given in Table I.

Table I. Basic Specification of ETA

Proton-beam energy	1.5 GeV
Time averaged proton beam current	10 mA
Pulse length	1 msec
Repetition rate	100 Hz
Duty cycle	10 %
Proton beam power	15 MW

Such a high-power proton linac is of great importance not only for nuclear transmutation, but also for various fields of basic-science. An intense neutron source, especially for neutron scattering (condensed matter research) and other neutron-beam experiments, would be among the most important and promising fields of utilization. It is important to consider one can take full advantage of such a high-power proton linac with a high repletion rate (100 Hz) and long pulse length (1 msec) for an intense neutron source. The present paper presents various possible applications.

2. Possible Neutron Sources

The various possible types of neutron sources using the proposed proton linac are listed in Table II. The first option is of the SINQ type, in which the pulse structure of the proton beam is completely ignored. From simple scaling one can expect a maximum time-averaged thermal neutron flux of the order of 3×10^{15} n/cm^2-sec, provided that a compact high-power target comprising of low neutron-absorbing heavy metal(s) can be developed.

Table II. Possible Neutron Source using ETA

Option	Type	Performer	Remarks
Full p-beam			non full-time
1	SINQ-Type	$\overline{\phi}_{th} \sim 3\times10^{15} n/cm^2 \cdot s$	
2	SNQ-Type	$\sim 3 * \phi_{th}^{SNQ}$	
3	μCF	$\overline{\phi}_{th} \sim 3\times10^{15} n/cm^2 \cdot s$	
H$^-$beam/Compressor ring			full-time
4	Pulsed Spallation N. S.	1-3MW	

The second option is of the SNQ type, in which the pulse structure of the proton beam can be utilized to some extent. However, the longer pulse length (1 msec) may decrease the merits of a time-modurated neutron source, as considered with SNQ. Further R&D studies concerning the target engineering will be necessary in order to utilize a higher beam power (15 MW).

The third option is a neutron source based on muon-catalyzed fusion (μCF); this type, however, is more or less in a state of art. The energy cost to produce one muon (about 10 GeV) and a cycle rate of about 100 (one muon can catalyze the D-T fusion reaction 100 times) has already been confirmed.[(2)] Although the energy cost is larger than that in the case of a spallation neutron source, the heat generated in a muon production target can be removed separately from a μCF target. We assumed a spherical μCF target having a radius of 20 cm in a large D_2O tank as SINQ. The absorption of slow neutrons in the target is the most serious neutronic problem regarding this type of neutron source. In the case of μCF, a target with a small absorption cross section can be considered. Although the neutron energy is higher (14 MeV) than in the case of spallation, it can be shown by a simple calculation that this neutron source can provide a maximum time-average thermal neutron flux of about 2×10^{15} n/cm^2-sec, as estimated in Table III.

Table III. Possible μCF Neutron Source using ETA

Energy cost (MeV/n)	$E_\mu/X_c \sim 100$
Neutron yield (10^{17} n/s-MW)	0.62
Average neutron energy (MeV)	14
Neutron leakage rate	1
Thermal neutron conversion efficiency (ϕ_{th}/Q)	2.24×10^{-3} (assuming R_c = 20 cm)
ϕ_{th}/P (10^{13} n/cm^2·s·MW proton beam)	14
ϕ_{th} (P = 15 MW)	2×10^{15}

The three options mentioned above require full-time and full-beam from the linac, if we are to aim at realizing one of the best intense neutron sources. It is, however, not realistic since the first priority of this linac is nuclear transmutation. We must therefore find a compromise in the beam intensity and/or the beam time. Such a compromise would make the new source less attractive.

The forth option is a pure pulsed spallation neutron source. In this case H^--beam acceleration and a compressor ring become indispensable. Generally, the simultaneous acceleration of H^- beam along with protons is feasible. One of the most important specifications is the beam current which can be obtained from an H^- ion source within the required beam emittance. Some important parameters which determine the beam power are listed in Table IV (parameters for JHP were given by Yamazaki(3)). In the linac considered for the Japan Hadron Project (JHP), rather modest, but more realistic, parameters are assumed, as listed in the first calumn of JHP. A time-average beam power of about 0.2 MW can be obtained under these assumptions. For a 1 MW beam, the typical specifications listed in the second column of JHP become necessary. At present, no H^--ion source is available which can satisfy such specifications.

Table IV. Important Parameters Determining the Beam Power

	JHP		ETA
Energy	1 GeV	1 GeV	1.5 GeV
Peak H^- current	20 mA	62 mA	20 mA
Emittance (90%, normalized)	1 πmm mrad	1 πmm mrad	1 πmm mrad
Beam pulse length	400 μs	500 μs	1000μs
Chopping factor	0.5	0.65	0.65
Repetition rate	50 Hz	50 Hz	100 Hz
Average beam power	0.2 MW	1 MW	2 MW

Although the detailed design for ETA has not yet been completed, we can compare here the parameters for ETA with those for JHP. One advantage of ETA is a longer pulse length (1 msec), which produces a higher beam power with a given peak current of the H^- beam. With the modest peak current assumed in JHP, we predict that a time-average beam current of 1.3 mA is possible. Since ETA will have FR power supplies with a higher powder than those for JHP, acceleration of H^- beams at this intensity will be easy. The maximum beam current acceptable in a compressor ring is determined by the space-charge limit. The present current is below this limit. If we can expect a higher peak current of the H^- beam (as listed in the second column of JHP), the average beam power can be increased up to 6 MW. In this case two identical compressor rings would be necessary.

3. Utilization of the Proposed Neutron Source

A higher proton beam energy (1.5 GeV) is quite acceptable. We studied by computer simulation the slow-neutron intensities as a function of the proton energy in the 0.8 - 3 GeV range, thus confirming that 1.5-GeV protons are as useful as those of 1.1 GeV (the minimum energy cost).(4)

How to use a high-power pulsed spallation neutron-source with a high repetition rate (100 Hz) is the next important problem. A high repetition rate (100 Hz) is usually thought to be too high for a pulsed neutron source for condensed-matter research. For simplicity, let's compare two cases: one is one 2-MW pulsed neutron source of 50 Hz; the other is two 1-MW sources, also operated at 50 Hz. There generally exists a finite idling time of the source due to target or moderator repair work, as well as of the instruments for sample-changing, temperature changing, etc (especially in the case of elastic scattering). When we take into account such idling losses, the total time-integrated net beam intensity from two half-power (1MW) sources is larger than that from the one full-power (2 MW) source. Although there should be some experiments or instruments which require the highest intensity, rather than the total time-integrated intensity, two half-power sources would be, at least, as useful as one source on the average, except for the disadvantage in the higher construction costs for the extra target station, additional instruments and another experimental hall. However, it must be mentioned that the accelerator is the most expensive component in spallation neutron facilities. There would exist various engineering merits for adopting multi target stations which share the full beam power. The life for the half-power target will be about 2-times longer than that for the full-power one, and further neutronic optimization would be possible in the case of multi-target stations. Although the optimal number of target stations and the optimal beam delivery scheme for each target station are other questions to be discussed, the choice is very flexible. In concluding, a high-power beam of 100 Hz can be usefully utilized with multi target stations.

4. Direct Use of Proton Pulses from the Linac

In neutron-scattering experiments using cold neutrons, the time-integrated-intensity of cold neutrons is sometimes more important than the pulse width.(5) Small-angle scattering (SANS), as well as CRISP-type, TOP-type experiments are of this category. The pulse length of protons directly obtained from the linac (1 msec) is sufficiently narrow for such experiments. For example, let's consider a SANS experiment using neutrons having a wavelength range of 4 - 10 Å with a total flight path length between the source and the detector of 10 m, which would be the shortest. The wavelength resolution in this experiment is about $\Delta\lambda/\lambda = 0.1 \sim 0.04$, which is quite acceptable. The wavelength resolution should usually be much better than the above values, since the total flight path length is longer than 10 m. If we take 10 direct proton pulses out of 100 pulses per second from the proton linac, the beam power becomes 1.5 MW, which means that this source can be the most intense pulsed cold neutron source operated at 10 Hz.

We developed a high-efficiency pulsed cold-neutron moderator, a liquid-hydrogen moderator with premoderator coupled to a reflector.(6) The combination of this moderator with the 1.5-MW pulsed spallation neutron source operated at 10 Hz should provide the cold-neutron flux given in Table V.

Table V. Intense Pulsed Cold Neutron Source using 10 pulses of Proton Beam from ETA

Fast neutrons per pulse	1.9×10^{16}
Fast neutrons per sec.	1.9×10^{17}
Cold neutron conversion efficiency (4π-equivalent cold Maxwellian neutron* flux on the moderator per fast neutron emitted from the target)	$\sim 0.96 \times 10^{-3}$
Time-averaged cold neutron flux ($n/cm^2 \cdot s$)	$\sim 1.8 \times 10^{14}$
Time-averaged neutron flux at Maxwellian peak (at ~2 meV) ($n/cm^2 \cdot s \cdot eV$)	$\sim 1.4 \times 10^{16}$
Pulse width of cold neutrons in FWHM (ms)	~ 1 ms
Pulse peak flux at Maxwellian peak ($n/cm^2 \cdot s \cdot eV$)	1.4×10^{18}

* Integrated flux over Maxwellian spectrum, ie. $\int_{Maxwell} \phi(E)dE$, not $\int_0^{0.005eV} \phi(E)dE$

Although the time-averaged cold-neutron flux is by about a factor 2 ~ 3 lower than that of ILL, the peak flux is about 20-times higher than that of ILL.

5. Concluding Remarks

We are keen to realize KENS-II (a part of JHP) as soon as possible. However, it has unfortunately not yet been financed. We are proposing a phased program for KENS-II while aiming at an earlier realization. Although the present proposal is independent of KENS-II, various possibilities for a future intense spallation neutron source should always be considered. In conclusion, if ETA is realized for the R&D of the nuclear transmutation techniques, we can consider one of the best pulsed neutron sources early in the next century.

References

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