Preliminary Design of a Multi-purpose Compact Accelerator-driven Neutron Source

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1. Introduction

A MuCANS (**Mu**lti-purpose **C**ompact **A**ccelerator-driven **N**eutron **S**ource) device, which is the portable and compact proton LINAC-based high-energy neutron source, is designed preliminarily for multi-purpose applications by using the high-energy neutrons. The initial target neutron yield of MuCANS device is ~10^{13} n/s (~10^6 n/cm^2·s at a distance position of 1m) with a proton beam of 2.5 MeV/10 mA through the nuclear reaction of ^{7}Li(p,n)^{7}Be. The MuCANS can support the industrial applications with the fast neutrons, and it will extend to the beam energy of about 30 MeV for the irradiation experiment of structural materials in the future fusion and fast-breeder reactors, afterwards. The MuCANS device is composed of an ECR ion source, an LEBT (low energy beam transport), an RFQ (radiofrequency quadrupole), a liquid Li-target, and neutron shielding structures in which the total weight of MuCANS device is less than 30 tons.

2. A Structure of MuCANS Device

The structure of portable MuCANS device is based on a proton LINAC for the production of high-energy neutrons with a steady-state long-pulse operation and high duty-cycle of 50%, as shown in Figure 1 [1]. A high-energy proton LINAC device, called as KOMAC (Korea Multi-purpose Accelerator Complex) facility, is operated successfully in KAERI (Korea Atomic Energy Research Institute) [2]. Thus, the MuCANS device is designed, fabricated, and operated by the development experience of KOMAC facility.

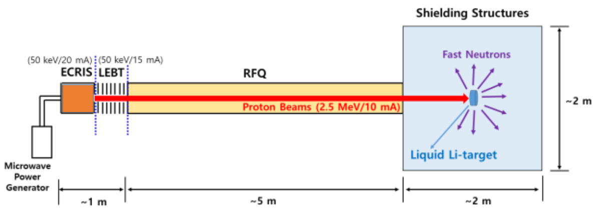


Fig. 1. Conceptual schematics of MuCANS device.

2.1 ECRIS (ECR Ion Source)

The hydrogen plasma and proton beam are produced and extracted by using a typical permanent magnet ECRIS (Electron Cyclotron Resonance Ion Sources) [3, 4]. An ECR resonance magnetic field of 875 Gauss is selected for a microwave frequency of 2.45 GHz with a maximum power of 2 kW. Prototype ECR ion sources are now being developed for the compact D-D neutron sources in KAERI, including the deuterium beam energies and currents of both 100 keV/100 mA and 200 keV/50 mA, as shown in Figure 2 [5]. The plasma density of prototype ECR ion sources is approximately 10^{10}~10^{11} cm^{-3}, including 2-open ECR surface and purely axial-field with magnetic confinements through the hexapole permanent magnet structure. The detailed major parameters of ECRIS are summarized for the MuCANS device in Table 1.

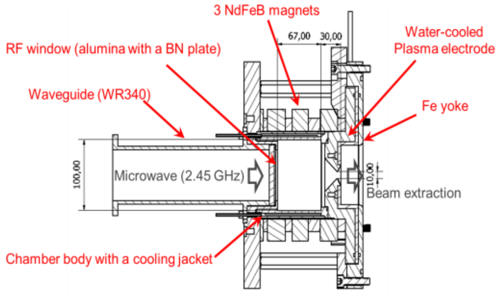


Fig. 2. The detailed structure of a prototype ECRIS for the compact D-D neutron sources in KAERI.

Table 1. Major Parameters of ECRIS

ECRIS	Target Value
ECR frequency/power [GHz/kW]	2.45 / 2.0
Working gas	H_2 (or D_2)
Plasma density [cm^{-3}]	~10^{11}
Operating pressure [mbar]	~ 10^5
Beam energy/current [keV/mA]	50 / 20
Aperture diameter [mm]	5
Proton fraction [%]	~ 90
Species ratio of H_2^+ & H_3^+ [%]	~ 10
Beam emittance (1σ RMS norm) [π ·mm·mrad]	~ 0.1

2.2 LEBT (Low Energy Beam Transport)

The purpose of LEBT (also called as an Injector) is to transport and match it for its injection into the next accelerating section which is an RFQ stage. At the end of LEBT, the transverse normalized RMS emittance has to be lower than 0.3 mm·mrad (with a target value of 0.25 mm·mrad) in order to reach the optimal beam transmission through an RFQ stage [6]. The LEBT of MuCANS device is an electrostatic multi-grid type for the compact system with a maximum beam loss of 25% (same as a beam current of 5 mA). Figure 3 shows an example of simulation code for the LEBT with an electrostatic multi-grid type [7]. The LEBT consists of an extraction gap and two Einzel lens, in total 6 electrodes. The two Einzel lenses give good control over the parameters at the entrance of the RFQ.

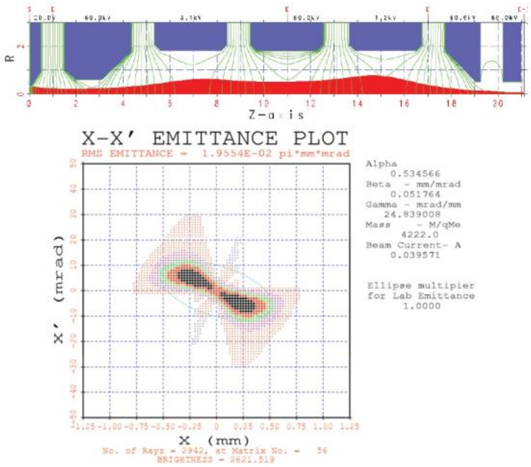


Fig. 3. Trajectory plot and emittance at the entrance of the RFQ for an example of LEBT.

2.3 RFQ (Radiofrequency Quadrupole)

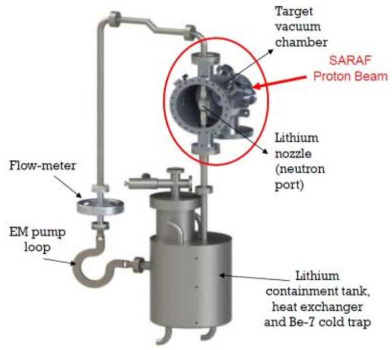
The RFQ is a main accelerator of extracted beams, transferred from the ECRIS and LEBT. The entrance beam current of RFQ is about 15 mA from the exit of LEBT. The structure of RFQ is conventional 4-vane accelerator, and the preliminary major parameters are listed in Table 2 [8].

Table 2. Major Parameters of RFQ

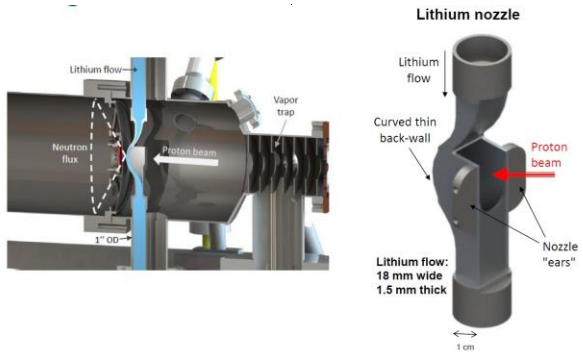
RFQ	Target Value
Input energy [keV]	50
Output energy [MeV]	2.5
Frequency [MHz]	162.5
Entrance beam current [mA]	15
Vane voltage [kV]	65
Vane length [cm]	523.4
Cavity power [kW, PEC]	103.14
Beam power [kW]	37.5
Averaged aperture [cm]	0.566
Transmission efficiency [%, $E_{\mathrm{limit}} = 0.05$]	99.6

2.4 Beam Target

A liquid Lithium(Li) target is considered for the production of fast neutrons in MuCANS device because of the higher reaction cross-section than the beryllium target. The low melting point of lithium and its compounds has been a major drawback in using the ^{7}Li(p,n)^{7}Be reaction with high-power accelerators [9]. Usage of conventional targets (metallic lithium or compounds such as lithium fluoride) with the cooling support has been usually limited to proton beam intensities of <100 μA. The blistering of target backing also sets a limit to high beam-power irradiation of solid lithium and beryllium targets. With the availability of higher beam intensities (in the range of milliamperes) from the modern LINACs, the development of lithium targets capable of sustaining high beam powers has been studied in SARAF (Israel) [10]. Figure 4 shows the circulation system of L-Li target, including a jet nozzle, and target chamber in the SARAF.



(a)



(b)

Fig. 4. (a) Circulation system of L-Li target, including a jet nozzle and (b) target chamber in the SARAF (Israel).

2.5 Neutron Shielding Structure

The neutron shielding structure consists of HDPE and Pb thick-plates for a proton beam of 2.5 MeV/10 mA and a neutron yield of ~10^{13} n/s. The initial calculation of shielding material thickness, estimated by using the MCNP code, will be done in near future [11]. For human dose limitation, 5 μSv/hr is used for upper limited value of shielding structures, according to the recommendation of ICRP-60 with a margin safety factor of two. Total weight of shielding structure around the beam target should be less than 15 tons to meet the portable and compact neutron source of MuCANS device. Then, final goal of total weight is 30 tons for

MuCANS device, including the shielding structure, accelerator, and sub-systems.

3. Model Devices

There are two model devices, investigated for development of the MuCANS device. One device is RANS2 device in RIKEN (Japan), and another device is LANSAR-PL4 device in AccSYS Technology Inc. (USA).

3.1 RANS2

Since the radiation level and the amount of shielding for a transportable compact neutron system for on-site use, a small system is appropriate and feasible to use. The neutron yield around a Be target is estimated to be ～10^{12} n/s with a current of 100 μA. The small compact neutron source was designed with a low energy proton beam to make the shielding much smaller than former device (called as RANS) by avoiding fast neutrons with energies greater than 1 MeV [12]. According to the Japanese radiation regulations, an ion beam accelerator whose energy is lower than 2.5 MeV can be operated without designating a radiation controlled area, except for deuteron beams or the insertion of a neutron-generating target material such as Be or Li, thus avoiding a high gamma ray dose. RANS2 is being developed and is equipped with a 2.49 MeV three-fold proton accelerator and Li target as the first test model of an on-site compact neutron system, particularly for outdoor use. To increase the neutron yield at a low acceleration energy, Li was chosen as a target instead of Be. Table 3 shows the main parameters of RANS2 device.

Table 3. Main Parameters of RANS2

RANS2	Target Value
Accelerated particle	p^+
Beam energy [nominal, MeV]	2.49
Beam current [μA]	100
Beam duration [μsec]	≤ 1,100
Pulse repetition rate [Hz]	10~180
Neutron production reaction	$^7Li(p, n)^7Be$
Maximum target yield [n/sec/4π]	~10^{12}
Maximum thermal flux [n/cm2/sec at 1m distance position]	$1.65E10^5$
Accelerator length [m]	< 5
Accelerator weight [ton]	3
Target & Shield weight [ton]	< 0.7
Accelerator type	LEBT + RFQ

3.2 LANSAR-PL4

The LANSAR generators provide a range of total neutron output from 10^8 to greater than 10^{13} n/s [13]. Neutrons are generated by the bombardment of rugged beryllium (Be) targets with energetic protons or deuterons. The low neutron energies available from the $^9Be(p,n)^9B$ and $^9Be(d,n)^{10}Be$ reactions reduce the moderator and shielding requirements for the production of thermal neutrons. Thus, the overall housing and space required for LANSAR neutron generators can be reduced. AccSYS's pulsed ion beam accelerators are also well suited for applications requiring a high flux of pulsed neutrons. Compact and reliable LANSAR neutron generators are well suited for day-to-day operations in non-destructive inspection and so on. Table 4 shows the main parameters of LANSAR-PL4 device.

Table 4. Main Parameters of LANSAR-PL4

LANSAR-PL4	Target Value
Accelerated particle	p^+
Beam energy [nominal, MeV]	3.9
Neutron yield [n/sec/μA]	$1.3E10^9$
Beam current/pulse [mA]	40
Beam pulse width [μsec]	25~215
Pulse repetition rate [Hz]	1~120
Neutron production reaction	$^9Be(p, n)^9B$
Maximum target yield [n/sec/4π]	$1.3E10^{12}$
Maximum thermal flux [n/cm2/sec]	$2.6E10^{10}$
Accelerator length [m]	4.2
Accelerator weight [ton]	3
Accelerator type	LEBT + RFQ

4. Conclusions

A portable (and/or movable) MuCANS (**Mu**lti-purpose **C**ompact **A**ccelerator-driven **N**eutron **S**ource) device, which is the LINAC-based high-energy neutron source, is designed preliminarily in KAERI for multi-purpose applications with the high-energy neutrons. At first, the preliminarily designed structures of MuCANS device are introduced, and then the detailed final design will be decided by further studies in near future. The beam energy of MuCANS device will also extend to ~30 MeV for the neutron irradiation test of structural materials in the future fusion and fast-breeder reactors.

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