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

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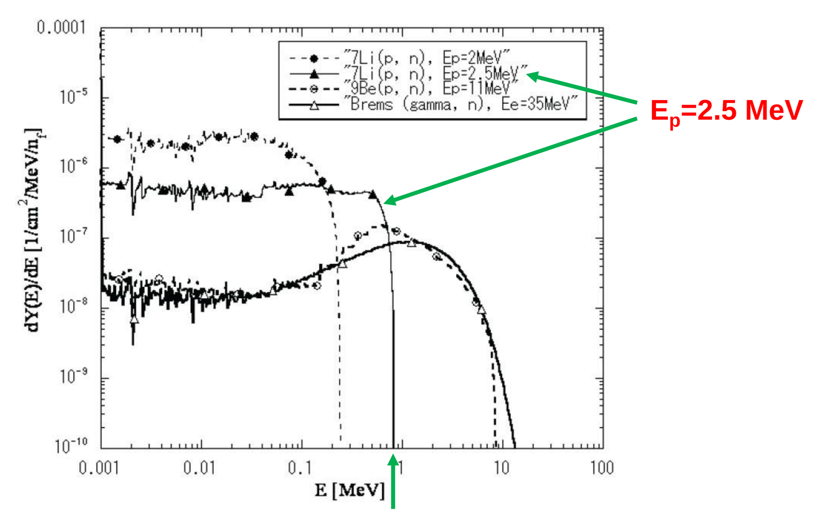
Introduction

- A MuCANS (Multi-purpose Compact Accelerator-driven Neutron Source) device in the KAERI (proposed)
  - A portable and compact proton LINAC-based high-energy neutron source
  - Target neutron yield: ~10^{13} n/s (~10^{6} n/cm²·s at a distance position of 1 m)
  - Nuclear reaction: $^{7}Li(p,n)^{7}Be$ (with Solid-state- or Liquid-Li target)
  - Final proton beam: 2.5 MeV/10 mA (25 kW)

- Common Nuclear Reactions & Neutron Energy Spectra

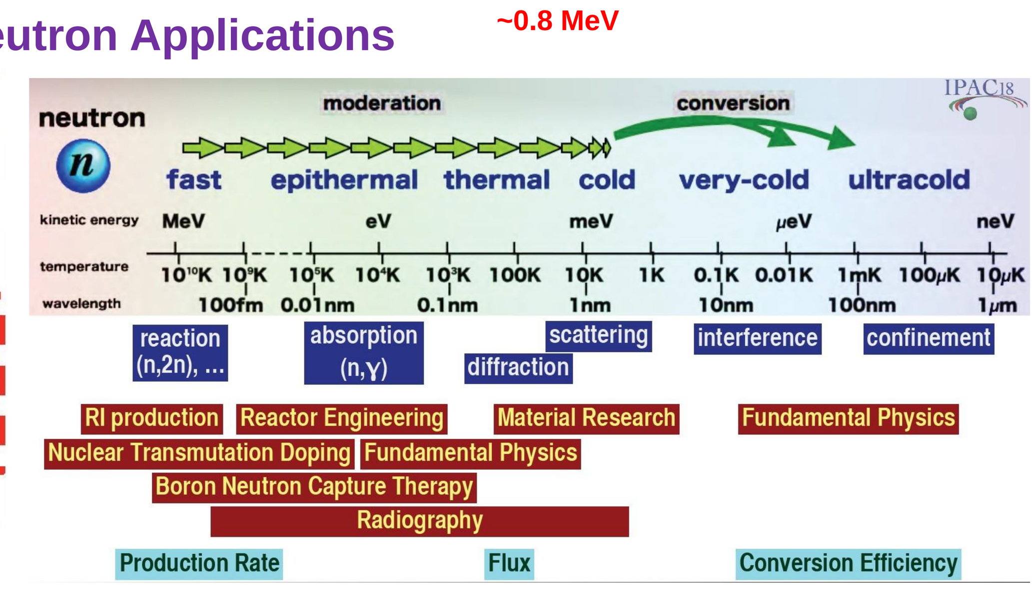
Reaction	Shorthand	Q Value [MeV]	Threshold Energy [MeV]	Minimum Product Energies [MeV]
$^{2}H + ^{2}H \rightarrow ^{3}He + n$	$^{2}H(d,n)^{3}He$	+3.269	NA	^{3}He: 0.82 n: 2.45 *
$^{2}H + ^{3}H \rightarrow ^{4}He + n$	$^{3}H(d,n)^{4}He$	+17.589	NA	^{4}He: 3.54 n: 14.05
$^{1}H + ^{7}Li \rightarrow ^{7}Be + n$	$^{7}Li(p,n)^{7}Be^{\dagger}$	-1.644	1.880	^{7}Be: 0.21 n: 0.03
	$^{1}H(^{7}Li,n)^{7}Be^{\dagger}$	-1.644	13.094	^{7}Be: 10.0 n: 1.44
$^{2}H + ^{7}Li \rightarrow ^{8}Be + n$	$^{7}Li(d,n)^{8}Be$	+15.031	NA	^{8}Be: 1.68 n: 13.35
$^{1}H + ^{9}Be \rightarrow ^{9}B + n$	$^{9}Be(p,n)^{9}B$	-1.850	2.057	^{9}B: 0.18 n: 0.023
$^{2}H + ^{9}Be \rightarrow ^{10}Be + n$	$^{9}Be(d,n)^{10}B$	+4.361	NA	^{10}B: 0.40 n: 3.96



- Neutron Source Characteristics & Neutron Applications

Reactions	Neutron Yield	Neutron Production*	Heat Release (MeV/n)	Remarks
Spallation	17-27n/p	10^{14} (n/s/cm²)	30-55	Expensive, complex, adamant usage
Fission	1 n/fission	10^{13}-10^{15} (n/s/cm²)	180	Expensive, complex, adamant usage
Giant laser inertial fusion	1 n/D-T pair	> 10^{16} (n/s/cm²)	Re-stockable D-T pellets	Unattainable?
$^{9}Be(D,n)^{10}Be$ $^{9}Be(p,xn)$	1 n/D 5x10^{-3} n/p	10^{13}-10^{15} (n/s/cm²)	1000 2000	Moderate cost, flexible operation, multipurpose
Photonuclear e-bremsstrahlung	5x10^{-2} n/e	10^{13} (n/s/mA)	2000	Moderate cost, flexible operation, multipurpose
Neutron Generators (D,D) (D,T)	10^{7}-10^{8} n/μC	10^{8} -10^{10} (n/s)	3500-10000	Transportable, affordable for tailored commercial applications, need higher flux
Table-top-laser photonuclear	10^{6}-10^{8} n/J	10^{8} -10^{10} (per shot)	Ultra-short pulsed lasers	Many debris, neutronics not yet matured
Neutristors solid-state, (D,D) chips	?	?	?	~$2000, tiny, implantable medically, to be developed

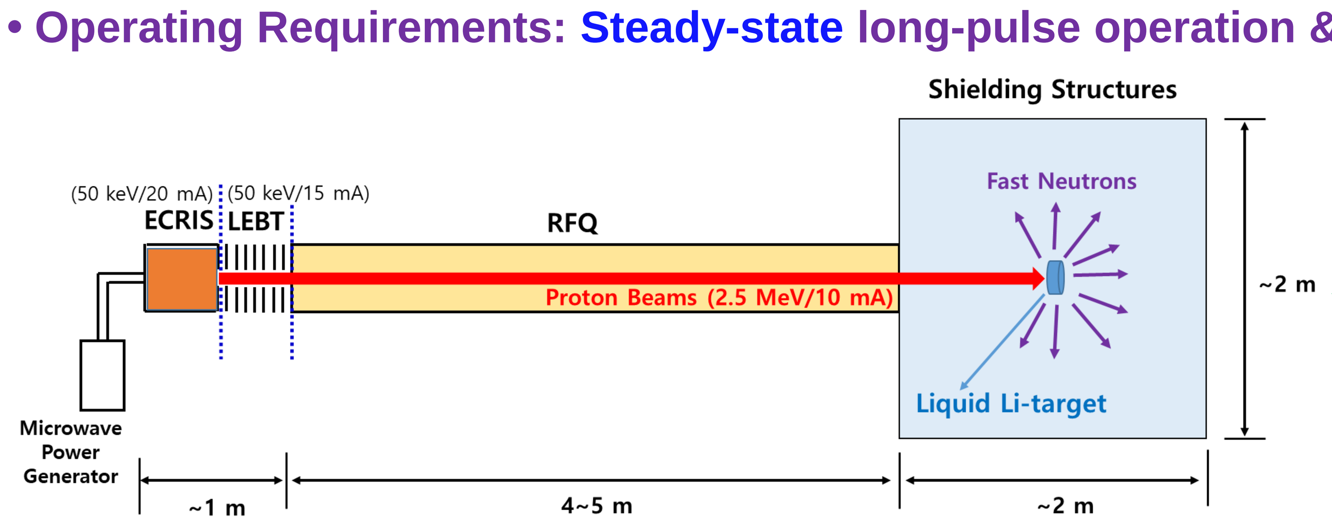
*need quantification of neutron spectral distribution and time structure



I. Main Components of the MuCANS Device

Characteristics of the MuCANS Device

- Operating Requirements: Steady-state long-pulse operation & Duty-cycle of > 50%



A Shielding Structure (example)

Fig. 1. Conceptual schematics of the MuCANS device

ECRIS (ECR Ion Source)

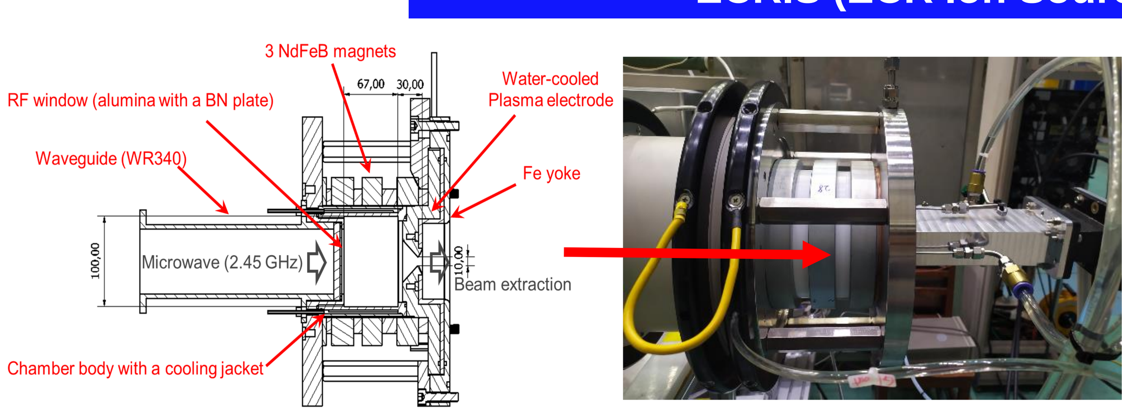


Fig. 2. A prototype ECRIS developed in KAERI for the compact D-D neutron generators

Table. 1. Main 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

LEBT (Low Energy Beam Transport)

- Operating Requirements
  - Transverse normalized RMS emittance < 0.3 π mm·mrad (with a target value of 0.25 π mm·mrad)
  - Maximum beam loss < 25% (same as a beam current of 5 mA)
  - Total 6 electrodes with one extraction gap & two Einzel lens (preliminary)

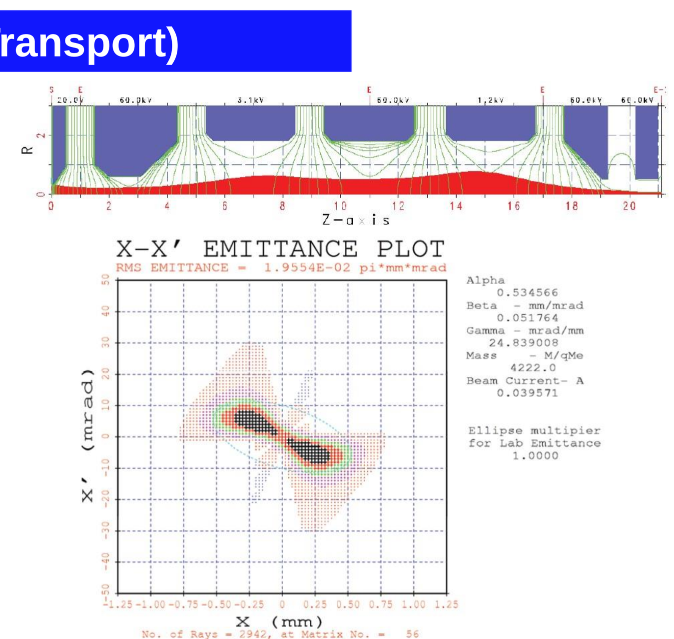


Fig. 3. Trajectory plot and emittance at the entrance of the RFQ for an example of LEBT

RFQ (Radiofrequency Quadrupole)

Table. 2. Main parameters of worldwide RFQs

Parameters	SNS	J-PARC	LINAC4	CSNS	KOMAC
Frequency	402.5MHz	324.0MHz	352.2MHz	324.0MHz	350.0MHz
Input / Output Energy	65keV / 2.5MeV	50keV / 3.0MeV	45keV / 3.0MeV	50keV / 3.0MeV	50keV / 3.0MeV
Peak current	38mA	50mA	70mA	40mA	20mA
Total length	3.76m	3.62m	3.06m	3.60m	3.25m
Kilpatrick	1.85	1.72	1.84	1.78	1.80
Emittance	0.21 pi mm-mrad	0.27 pi mm-mrad	0.25 pi mm-mrad	0.22 pi mm-mrad	0.22 pi mm-mrad
Duty factor	6%	3%	10%	1.05%	24%

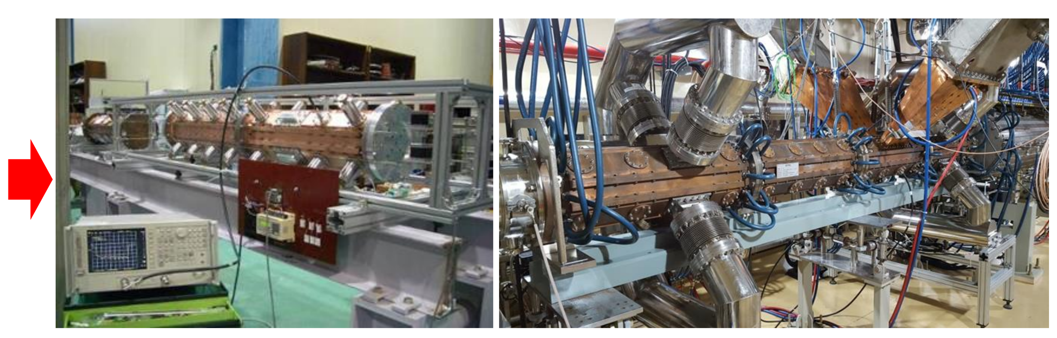


Fig. 4. An RFQ for the KOMAC in KAERI

Beam Target

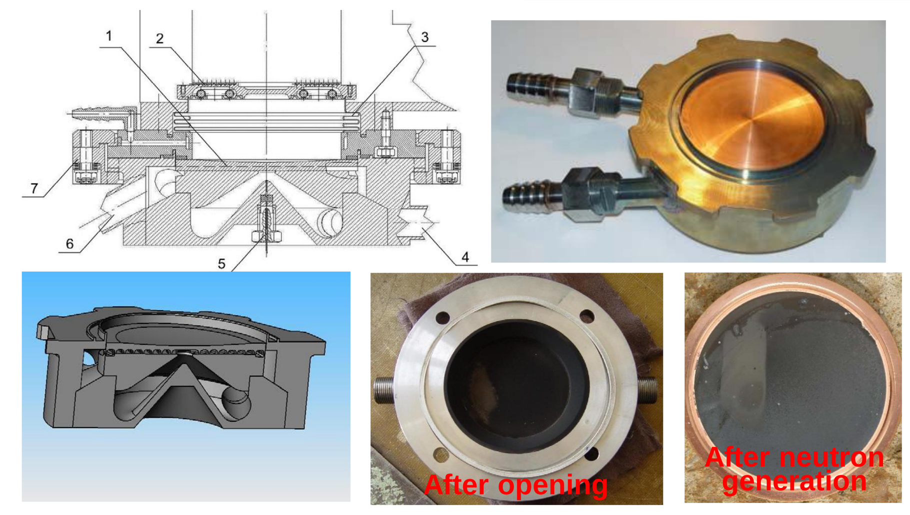


Fig. 5. Solid-state Li-Target of the BINP (Russia) (E_p=1.9~2.5 MeV, I_p=10 mA CW)

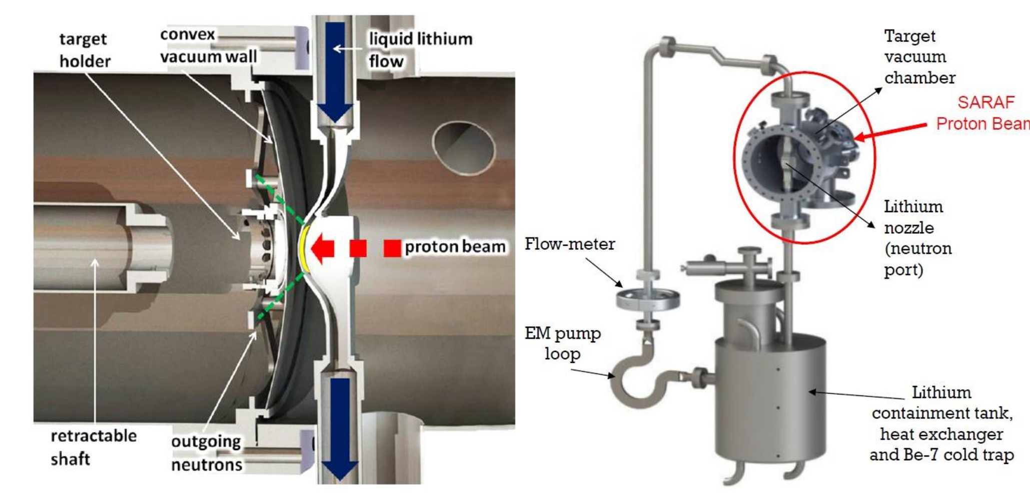


Fig. 6. Liquid Li-Target of the SARAF-I (Israel) (E_p=1.5~4 MeV, I_p=0.04~2 mA CW)

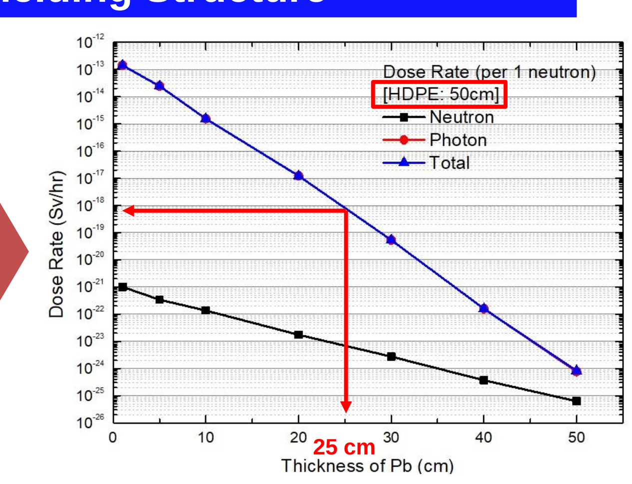
Neutron Shielding Structure

*Preliminary calculation by Dr. Do Heon Kim (KAERI)

- 타켓: $^{7}Li(p,n)^{7}Be$
- 차페 목표선량: 5μSv/hr
- 중성자원: point isotropic source, 0.4~0.8MeV (0.8MeV 가정)
- 고속중성자 수율: 1E+11, 1E+12, 1E+13, 1E+14, 1E+15
- 차페체: HDPE for neutron, Pb for photon
- 중성자 수율에 따른 Tally 요건

MCNP Tallys Needed:	5.00E−17	Sv/hr for	1.00E+11	n yields
	5.00E−18		1.00E+12	
	5.00E−19		1.00E+13	
	5.00E−20		1.00E+14	
	5.00E−21		1.00E+15	

- 모델링: MCNP6/F5 Tally



장치가 설치되는 건물의 콘크리트 벽두께에 의해 Pb-두께를 줄일 수 있음!

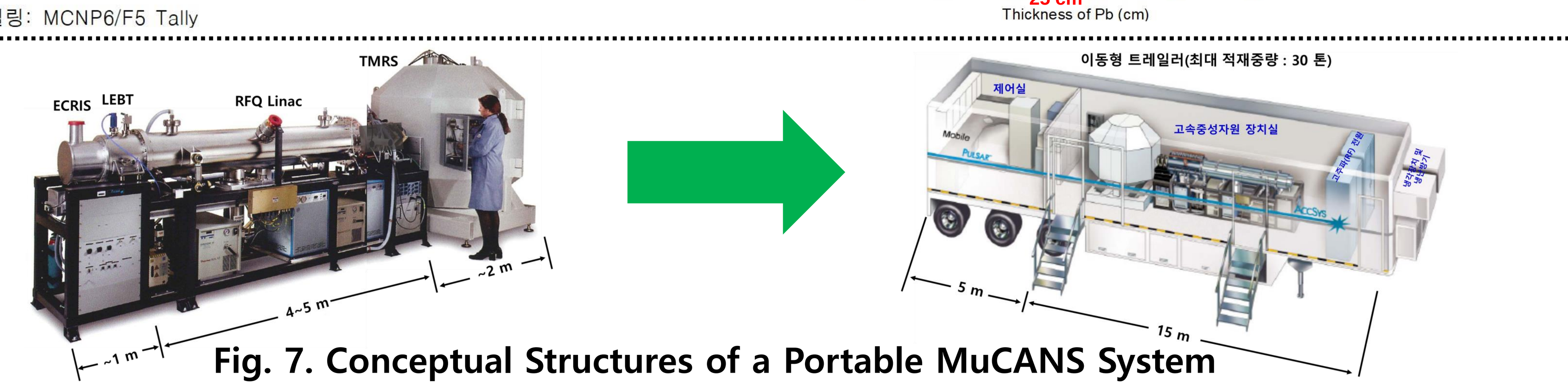


Fig. 7. Conceptual Structures of a Portable MuCANS System

III. Model & Reference Devices

Table. 3. Main parameters of RANS-2 (Japan)

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	$^{7}Li(p, n)^{7}Be$
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

일본의 방사선안전 규제에 의해 결정됨

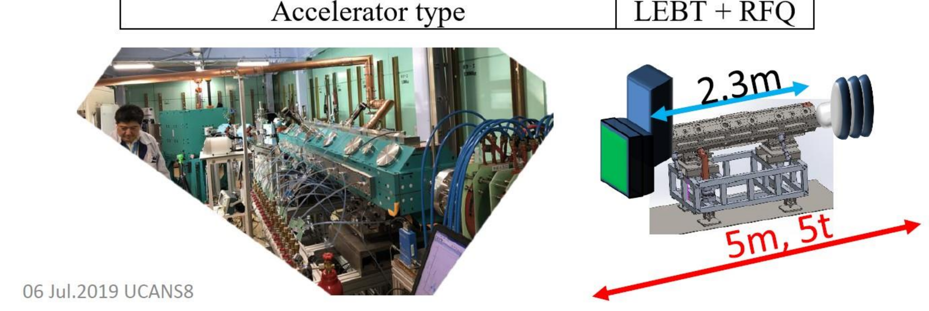
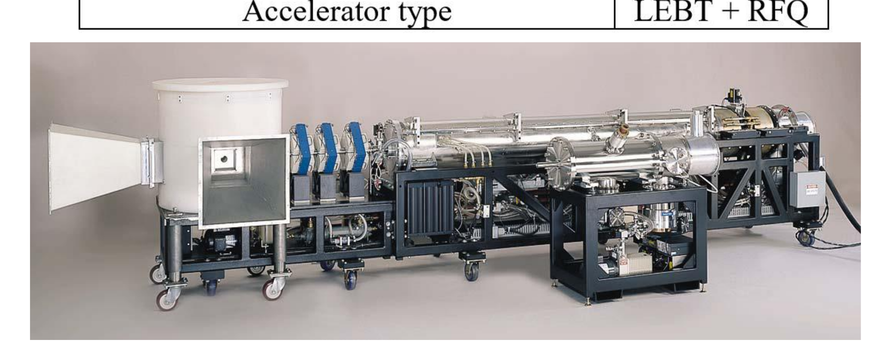


Table 4. Main parameters of LANSAR-PL4 (USA)

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	$^{9}Be(p, n)^{9}B$
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



Conclusions

- A portable (and movable) MuCANS (Multi-purpose Compact Accelerator-driven Neutron Source) device is designed preliminarily in KAERI
  - LINAC-based high-energy neutron source
  - Multi-purpose applications with the high-energy neutrons
- Detailed (final) design will be decided by further studies in near future
- Beam energy/current of MuCANS device will be also extended up to 30~40 MeV/100 mA
  - Neutron irradiation test of structural materials for the future fusion & fast-breeder reactors

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