# Quasi-monoenergetic high energy neutron fields: present status and future prospects

**Andy Buffler**

DEPARTMENT OF PHYSICS
UNIVERSITY OF CAPE TOWN

CCRI

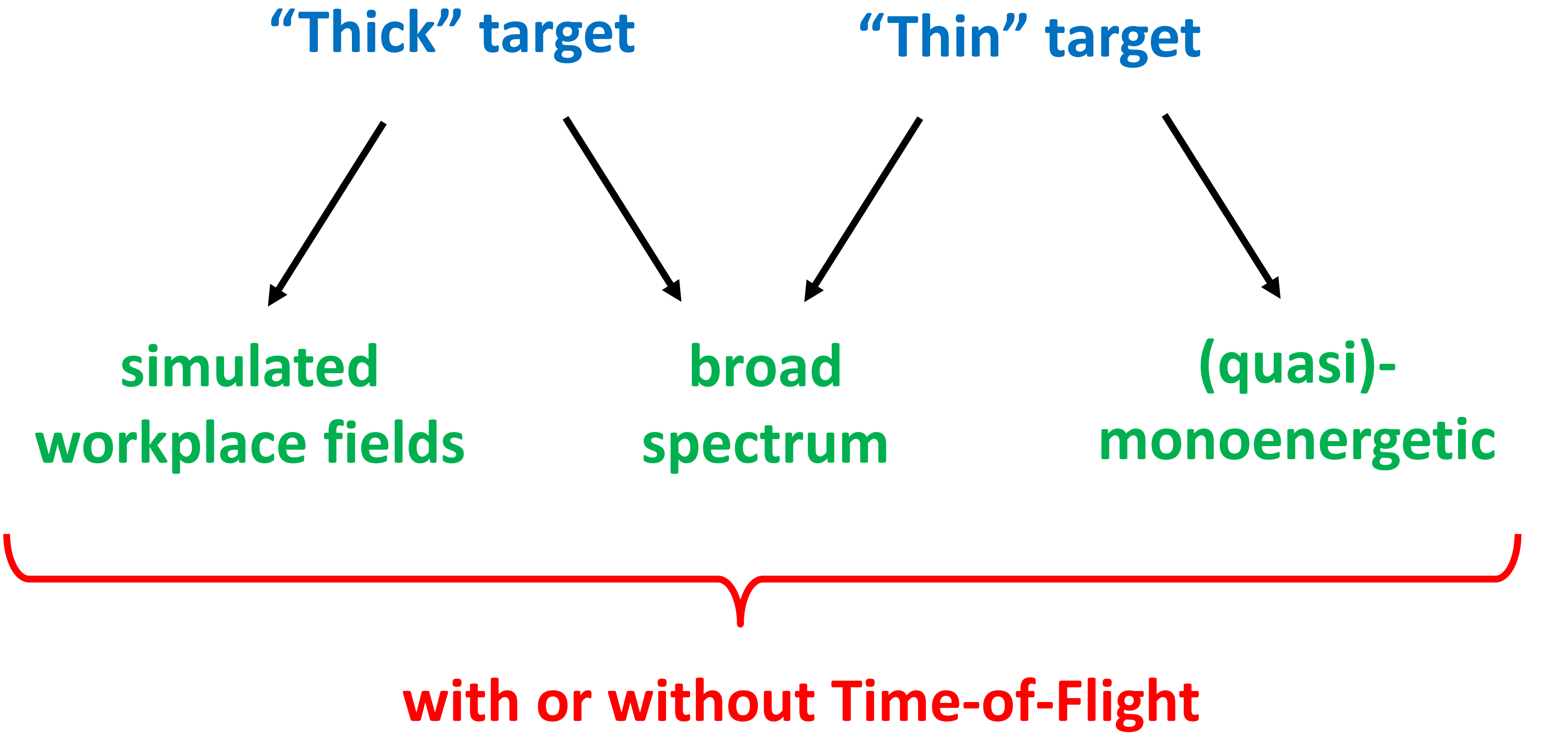
IAEA International Atomic Energy Agency

**nBHEAM2025**

**Neutron Beams at High Energy: Applications and Metrology**

7-8 July 2025, IAEA Headquarters, Vienna

# Accelerator-based neutron fields

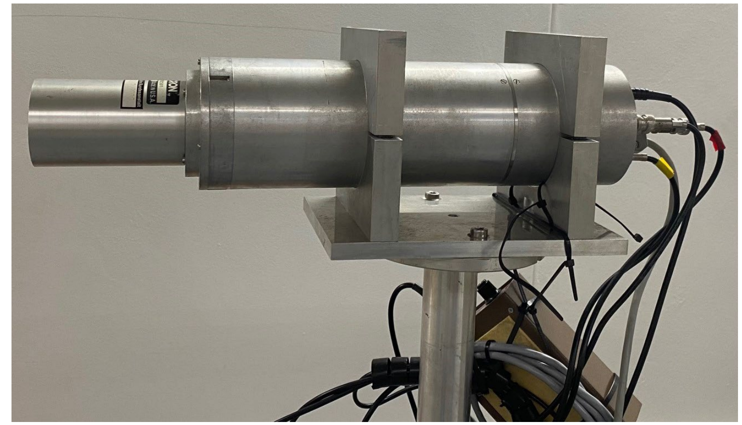


**Do we need (quasi)monoenergetic fields (as well as broad energy fields)?**

**Why "quasi"?**

# Spectral fluence typically measured with a liquid scintillator: NE-213 / BC-501A / EJ-301

iThemba LABS version:

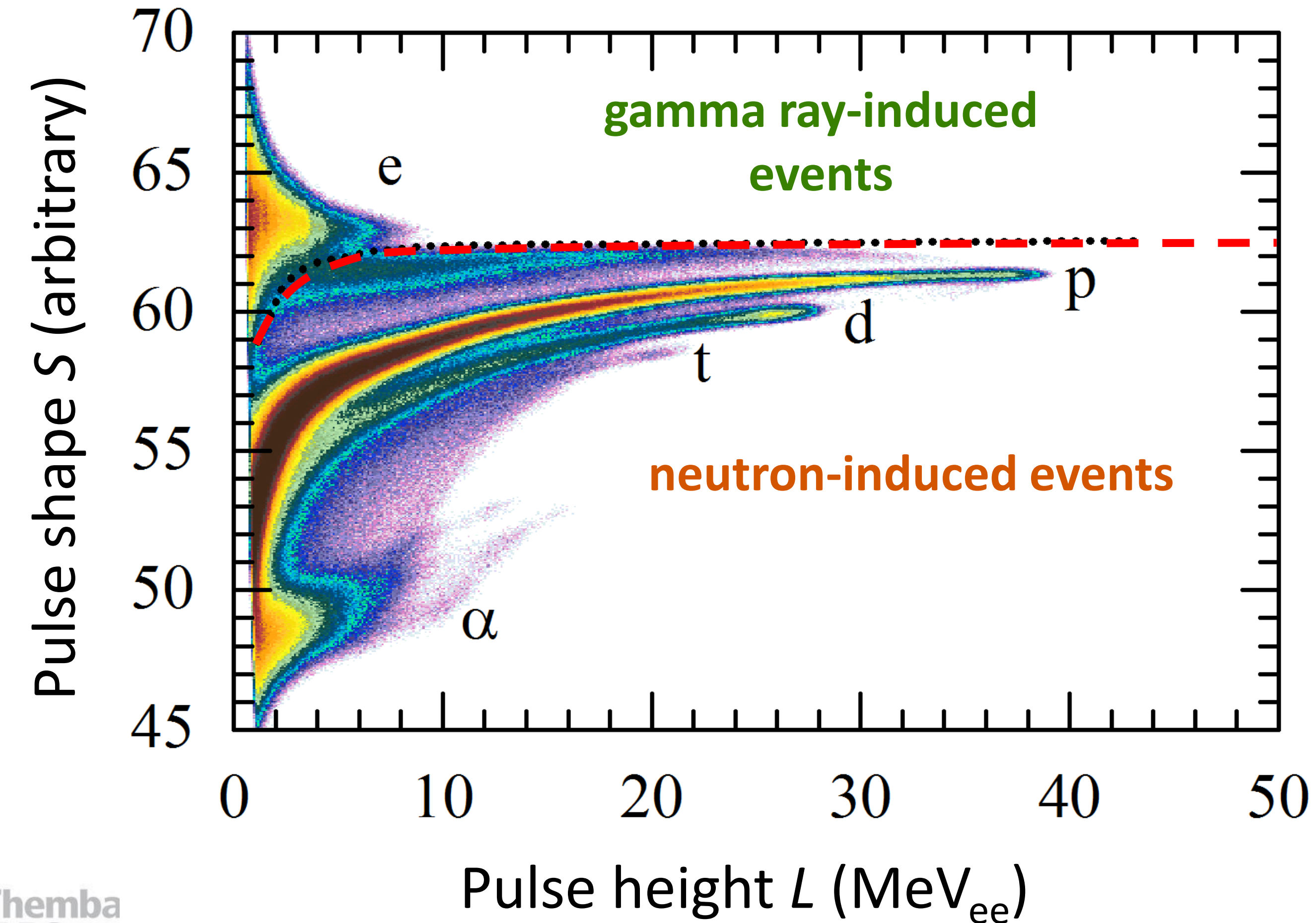


Data are recorded in coincidence in list mode using the standard NIM-based acquisition systems or modern digital systems:

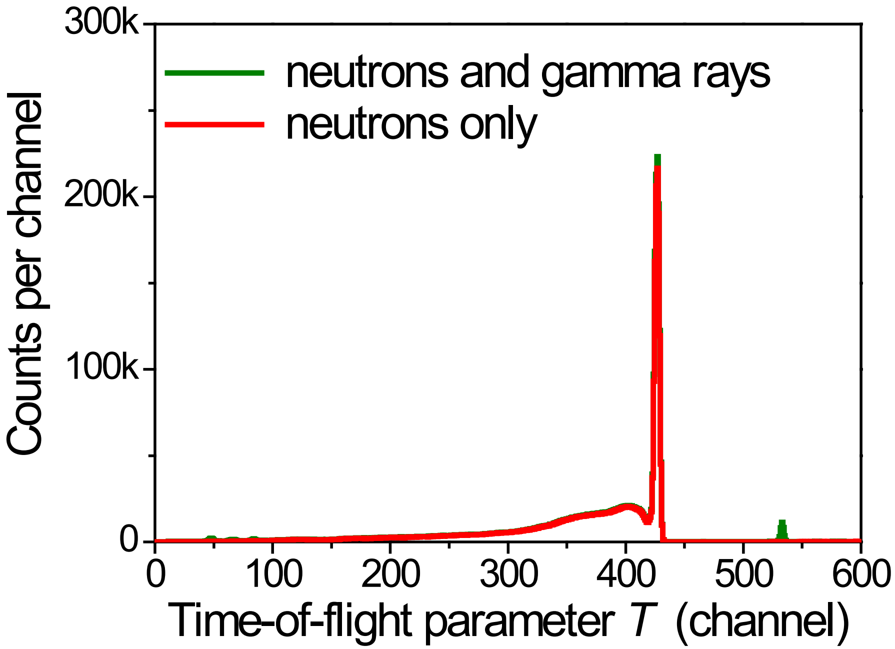
- Pulse height *L*
- Pulse shape *S*
- Time-of-flight *T*

… usually combined with a reference fluence measurement (e.g. U fission chamber), and data from beam monitors.

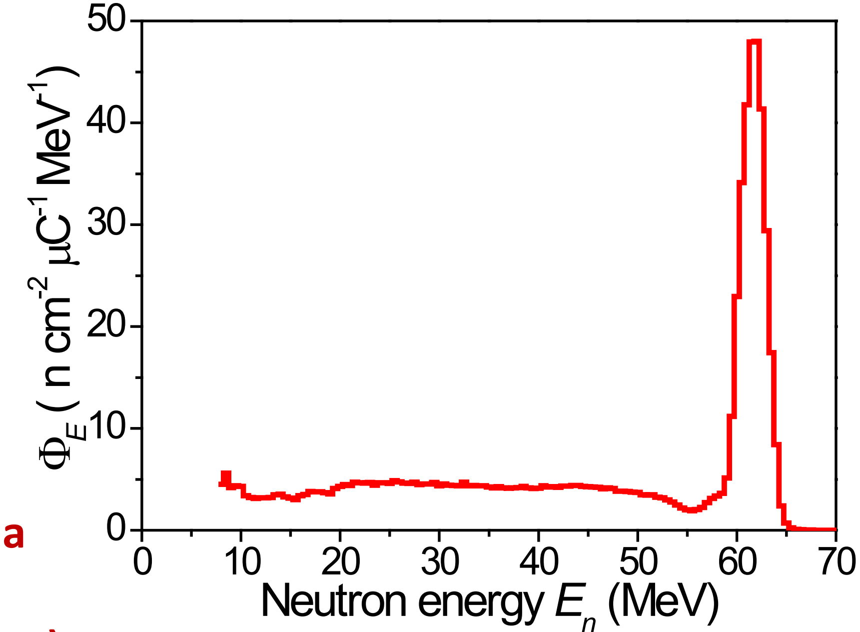
# Neutrons and gamma-rays produced by a 66 MeV proton beam irradiating a 6.0 mm Li target, measured by a 2" x 4" BC-501A detector at 0°.




National Research Foundation
iThemba LABS
Laboratory for Accelerator Based Sciences



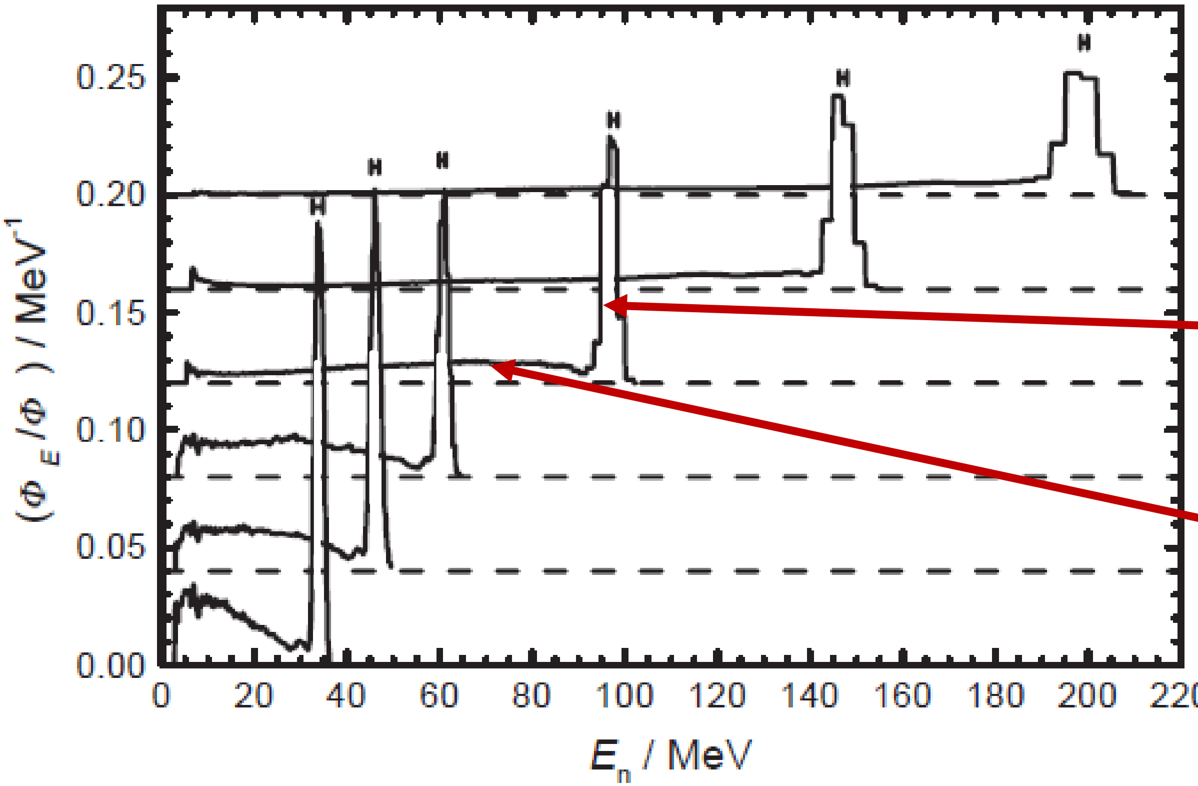

- Calibrate time scale
- Apply PSD
- Set pulse height threshold
- Rebin to energy
- Correct for efficiency
- Scale to fluence




**Energy spectrum of neutrons produced by a 66 MeV proton beam irradiating a 6.0 mm Li target (measured with NE-213 at 8 m).**

# Quasi-monoenergetic beams

## $^7Li(p,n)^7Be$ is often used ($Q$ = -1.6 MeV)




**direct reaction peak (g.s + 0.43 MeV)**

**continuum (break up)**

Radiation Protection Dosimetry (2004), Vol. 110, Nos 1-4, pp. 97–102
doi:10.1093/rpd/nch195

**QUASI-MONOENERGETIC NEUTRON REFERENCE FIELDS IN THE ENERGY RANGE FROM THERMAL TO 200 MeV**

R. Nolte[1,*], M. S. Allie[2], R. Böttger[1], F. D. Brooks[2], A. Buffler[2], V. Dangendorf[1], H. Friedrich[1], S. Guldbakke[1], H. Klein[1], J. P. Meulders[3], D. Schlegel[1], H. Schuhmacher[1] and F. D. Smit[4]
[1]Physikalisch-Technische Bundesanstalt, P.O. Box 3345 D-38116 38023 Braunschweig, Germany
[2]Physics Department, University of Cape Town, Rondebosch, 7700, South Africa
[3]Institut de Physique Nucléaire, Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
[4]iThemba Laboratory for Accelerator-Based Sciences, Somerset West, 7129, South Africa

# Time-of-flight measurement of neutrons produced by an 80 MeV proton beam irradiating a 10.0 mm Be target (with BC-501A at 8.00 m).

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Available online at www.sciencedirect.com

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Nuclear Instruments and Methods in Physics Research B 240 (2005) 617–624

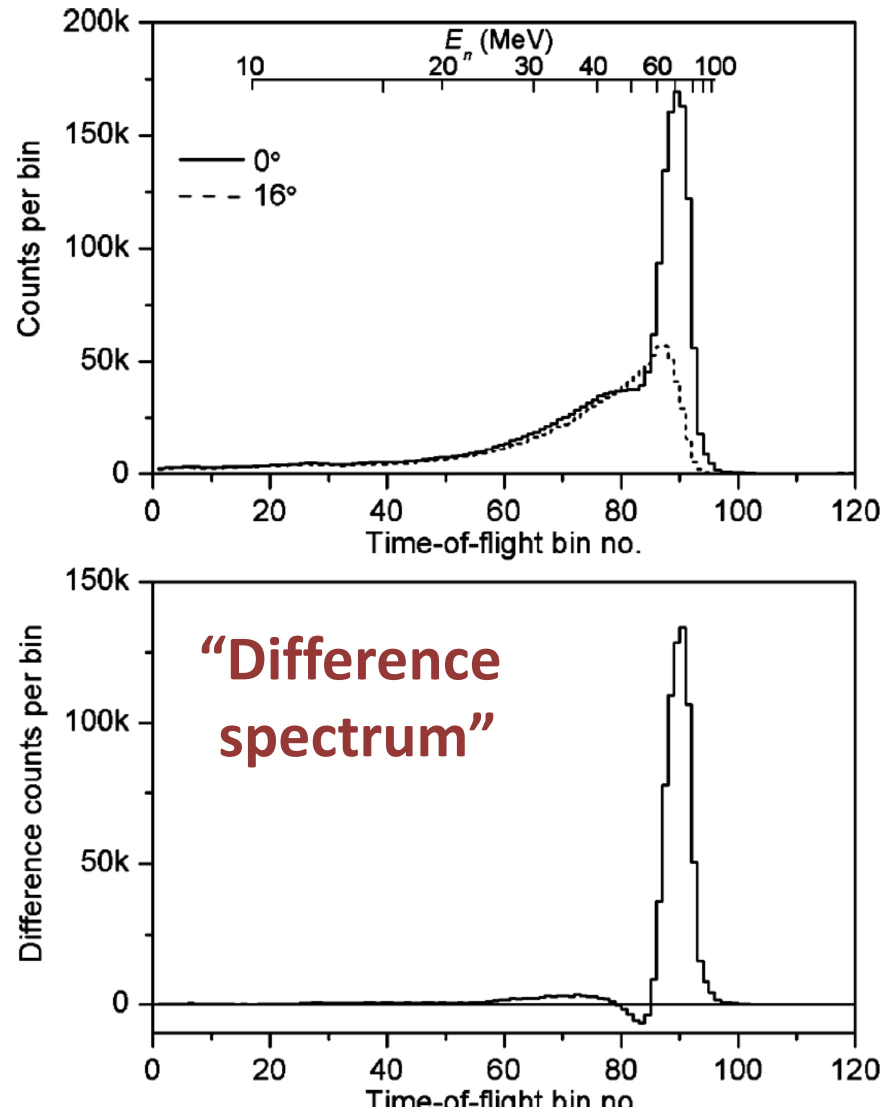
NIM B
Beam Interactions with Materials & Atoms

www.elsevier.com/locate/nimb

Cross-section measurements for neutron-induced reactions in copper at neutron energies of 70.7 and 110.8 MeV

J.M. Sisterson [a,*], F.D. Brooks [b], A. Buffler [b], M.S. Allie [b], D.T.L. Jones [c], M.B. Chadwick [d]

[a] Northeast Proton Therapy Center, Massachusetts General Hospital, 30 Fruit Street, Boston, MA 02114, USA and the Harvard Medical School
[b] Department of Physics, University of Cape Town, Rondebosch, South Africa
[c] iThemba LABS, Box 722, Somerset West 7129, South Africa
[d] Advanced Simulation and Computing, Los Alamos National Laboratory, Los Alamos, NM 87544, USA



# Global menu
# Quasi-monoenergetic HE neutron fields

| Facility | | | $E_p$ (MeV) | Pulsing | Neutron beam angle | ToF path (m) |
|---|---|---|---|---|---|---|
| | | | | | | |
| iThemba LABS | | South Africa | 35-200 | ns | 0 and 16 | 10 |
| RCNP | | Japan | 100-400 | ns | 0 to 30 | 100 |
| TIARA | | Japan | 40-90 | ns | 0 | 13 |
| CYRIC | | Japan | 20-90 | ns | 0 | ? |
| CIAE | | China | 75-100 | DC | 0 | (3) |
| IRIS | | Korea | 83 | ns | 0 | 50 |
| NFS | | France | 20-33 | ns | 0 | 28 |
| NPI | | Czech Rep | 18-36 | ns | 0 | 5 |
| Future facilities ? | | | | | | |

*Metrologia* **48** (2011)

IOP Publishing — Metrologia

Metrologia **48** (2011) S292–S303 — doi:10.1088/0026-1394/48/6/S06

# Quasi-monoenergetic high-energy neutron standards above 20 MeV

**Hideki Harano[1] and Ralf Nolte[2]**

[1] National Metrology Institute of Japan (NMIJ), Japan
[2] Physikalisch-Technische Bundesanstalt (PTB), Germany

Received 28 March 2011, in final form 20 June 2011
Published 28 October 2011
Online at stacks.iop.org/Met/48/S292

**Abstract**
This paper provides an overview of high-energy quasi-monoenergetic neutron sources and facilities above 20 MeV around the world. Various technical matters are discussed which are required in characterizing the neutron fields by spectrometry, fluence and beam profile measurements. Important topics regarding the calibration of neutron detectors are also introduced with emphasis on beam monitoring, tail correction, background subtraction and fluence-to-dose conversion. Efforts to standardize the high-energy neutron fluence in Japan and by the German national metrology institute in collaboration with Belgian and South African institutions are also presented.

# Two useful documents

EURADOS
European Radiation Dosimetry Group e. V.

EURADOS Report 2013-02
Braunschweig, May 2013

*EURADOS Report* **2013-02** (2013

## High-energy quasi-monoenergetic neutron fields: existing facilities and future needs

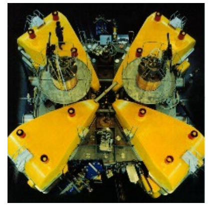
Pomp S., Bartlett D.T., Mayer S., Reitz G., Röttger S., Silari, M., Smit F.D., Vincke H., and Yasuda H.

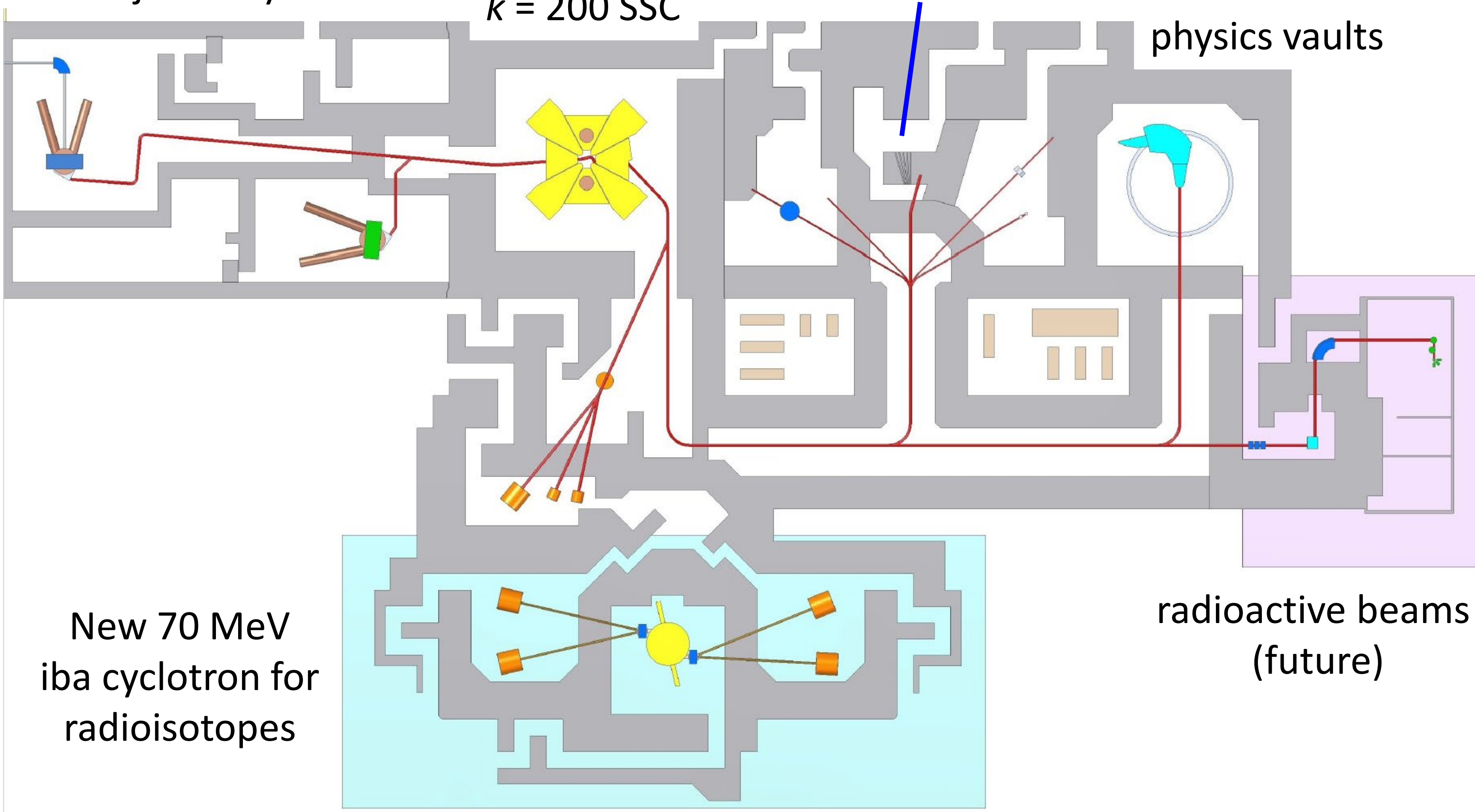
ISSN 2226-8057
ISBN 978-3-943701-04-3

# iThemba LABS, Cape Town, South Africa

National Research Foundation

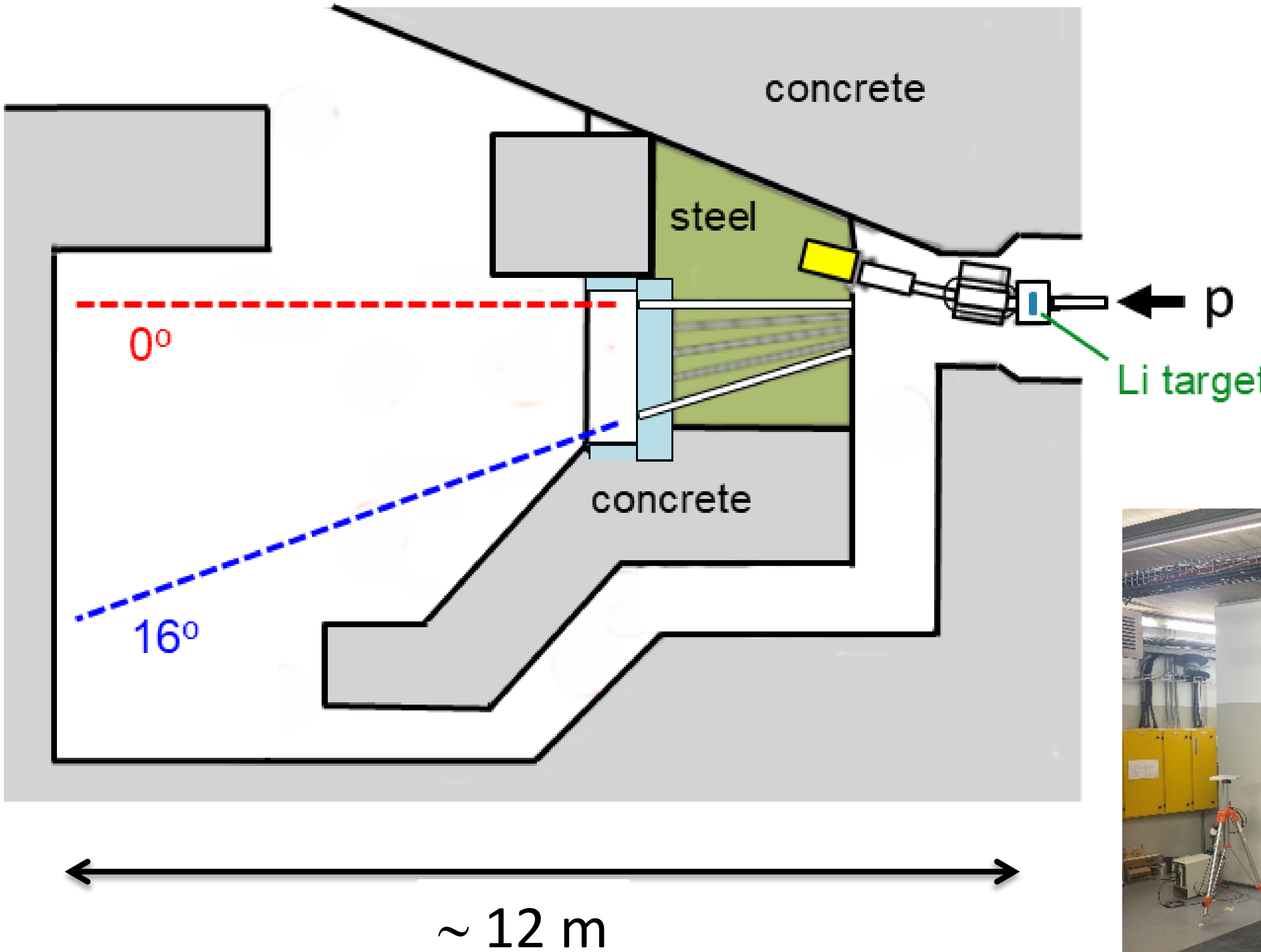
iThemba LABS
Laboratory for Accelerator Based Sciences





# Fast neutron beam facility at iThemba LABS

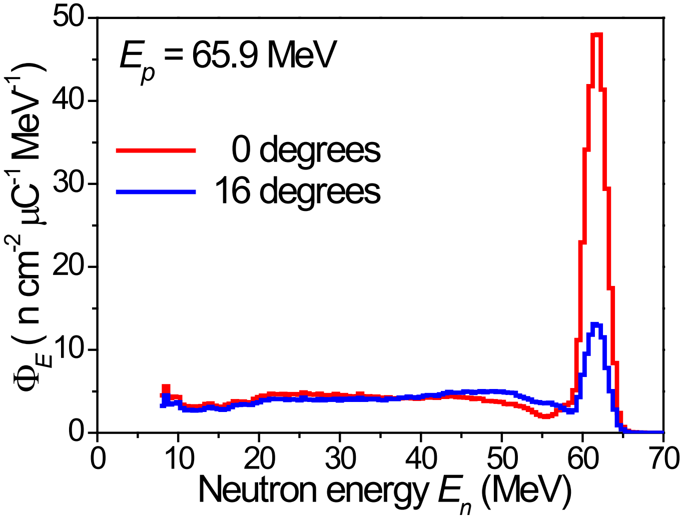
Cape Town, South Africa

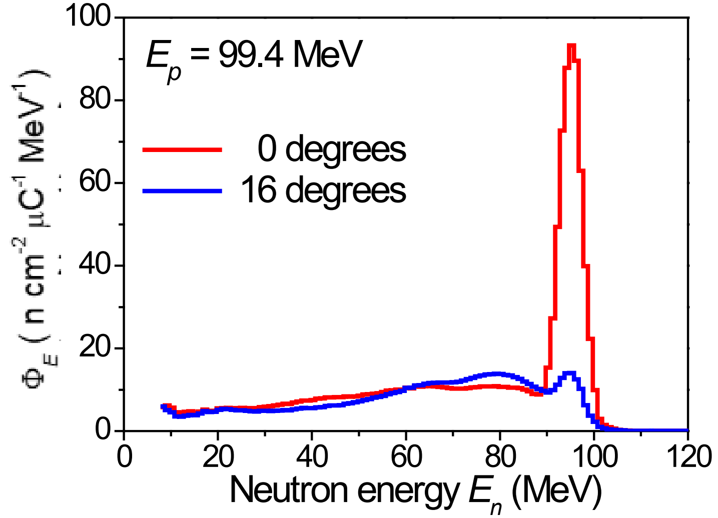


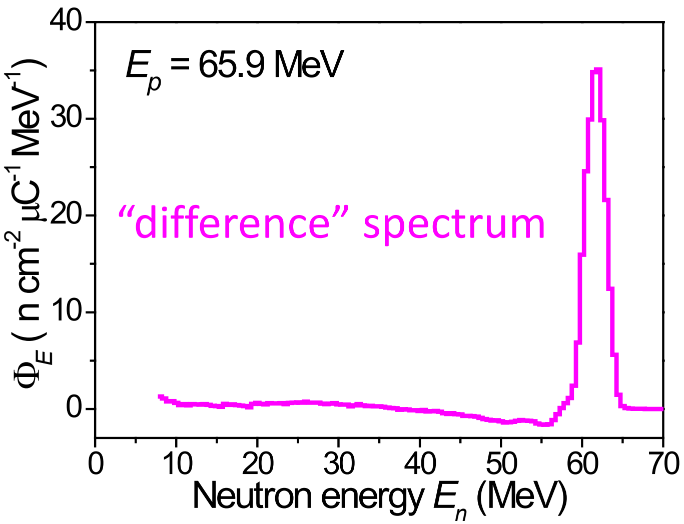

- $k$ = 200 cyclotron
- neutrons via Li(p,n)
- ns-pulsed beams
- quasi-monoenergetic neutron beams 30-200 MeV

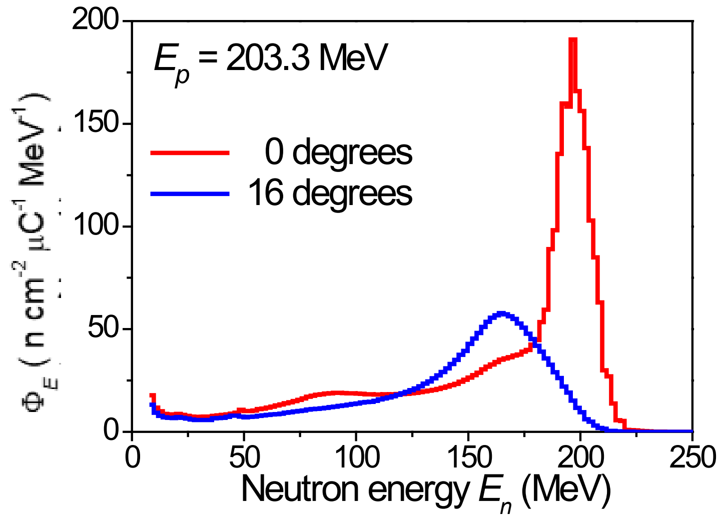
# iThemba LABS

## Energy spectra of neutrons produced by proton beams irradiating a 6.0 mm Li target (measured with NE-213 at 8 m).

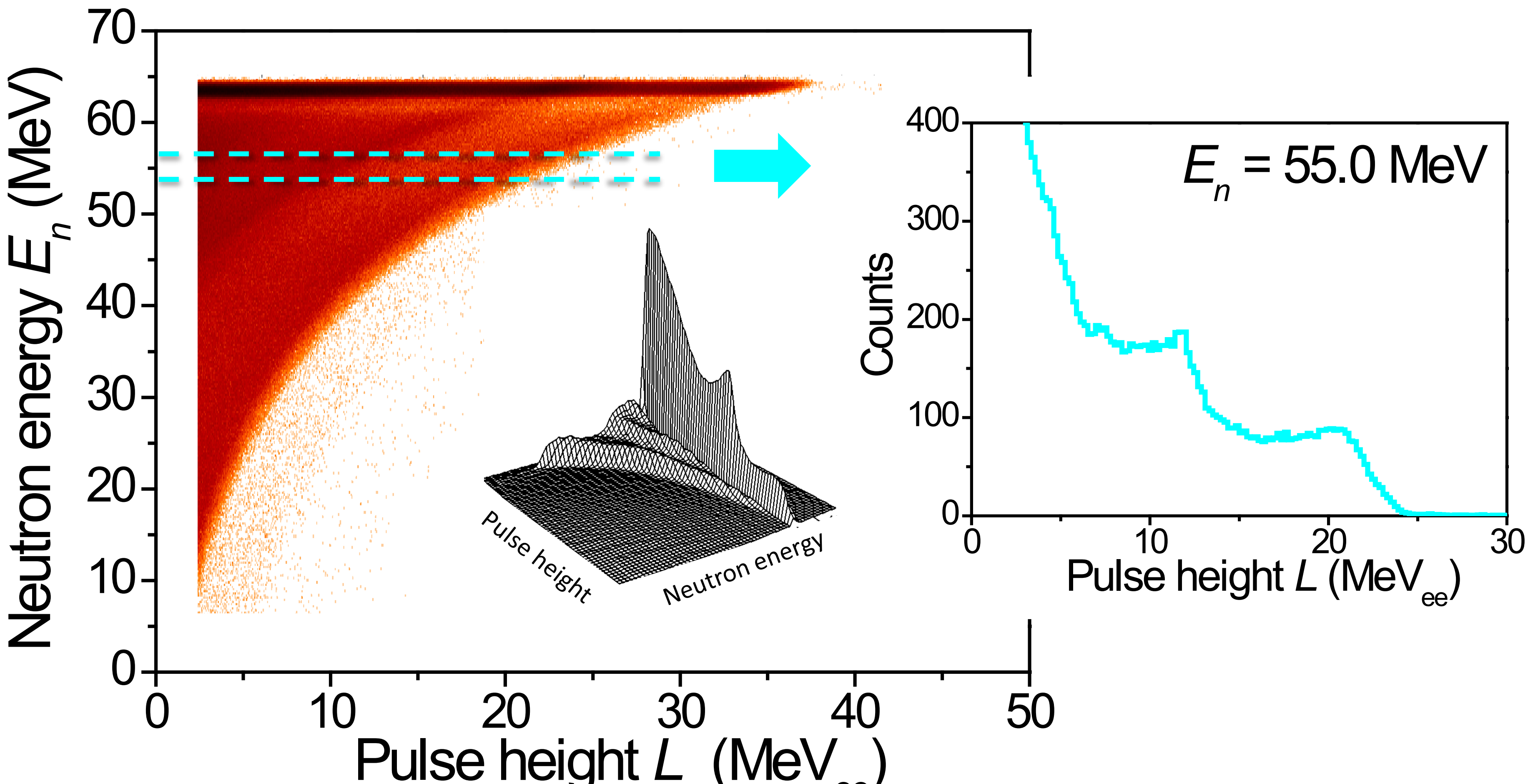


# Measurements of neutron energy of neutrons (via Time-of-Flight) produced by a 66 MeV proton beam irradiating a 6.0 mm Li target. (with 2” x 4” BC-501A detector at 8.00 m from the target at 0°).

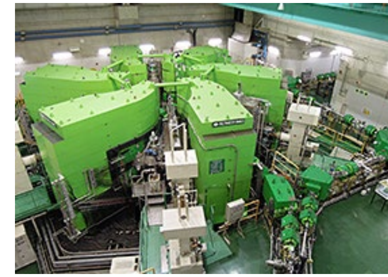


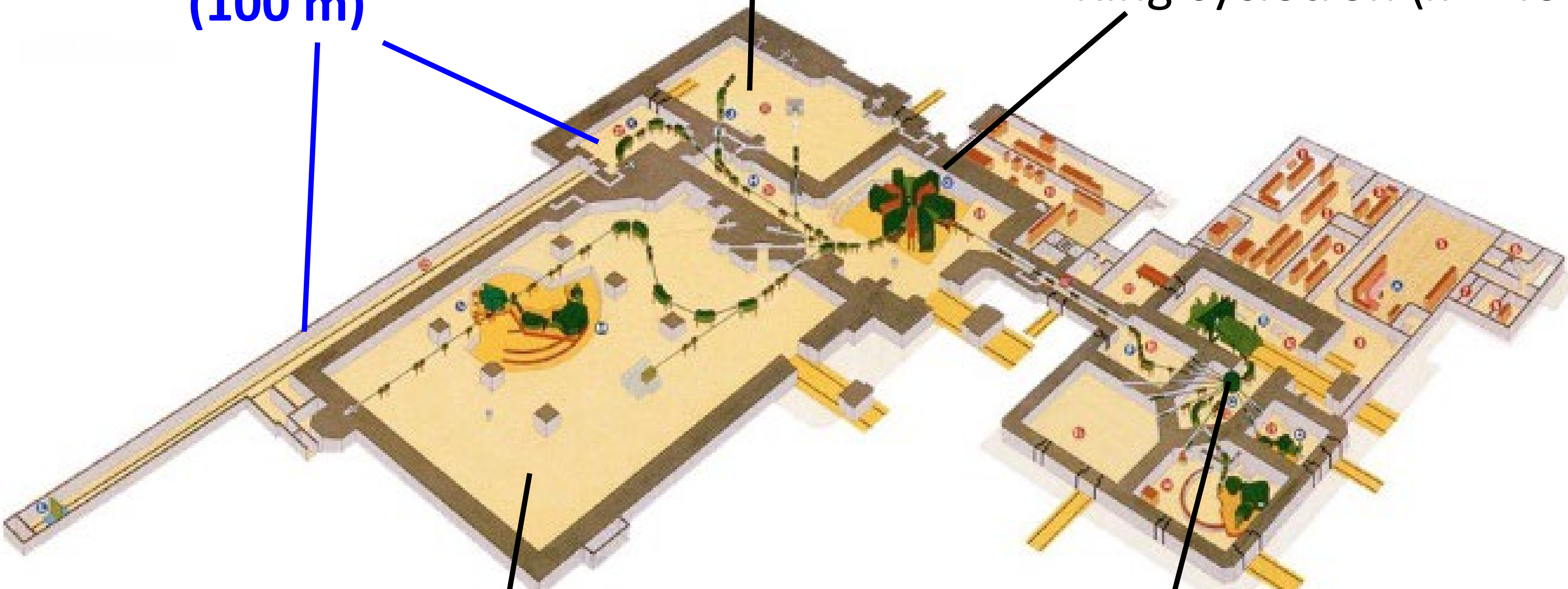

DEPARTMENT OF PHYSICS
UNIVERSITY OF CAPE TOWN

NRF National Research Foundation | iThemba LABS Laboratory for Accelerator Based Sciences

# Research Center of Nuclear Physics

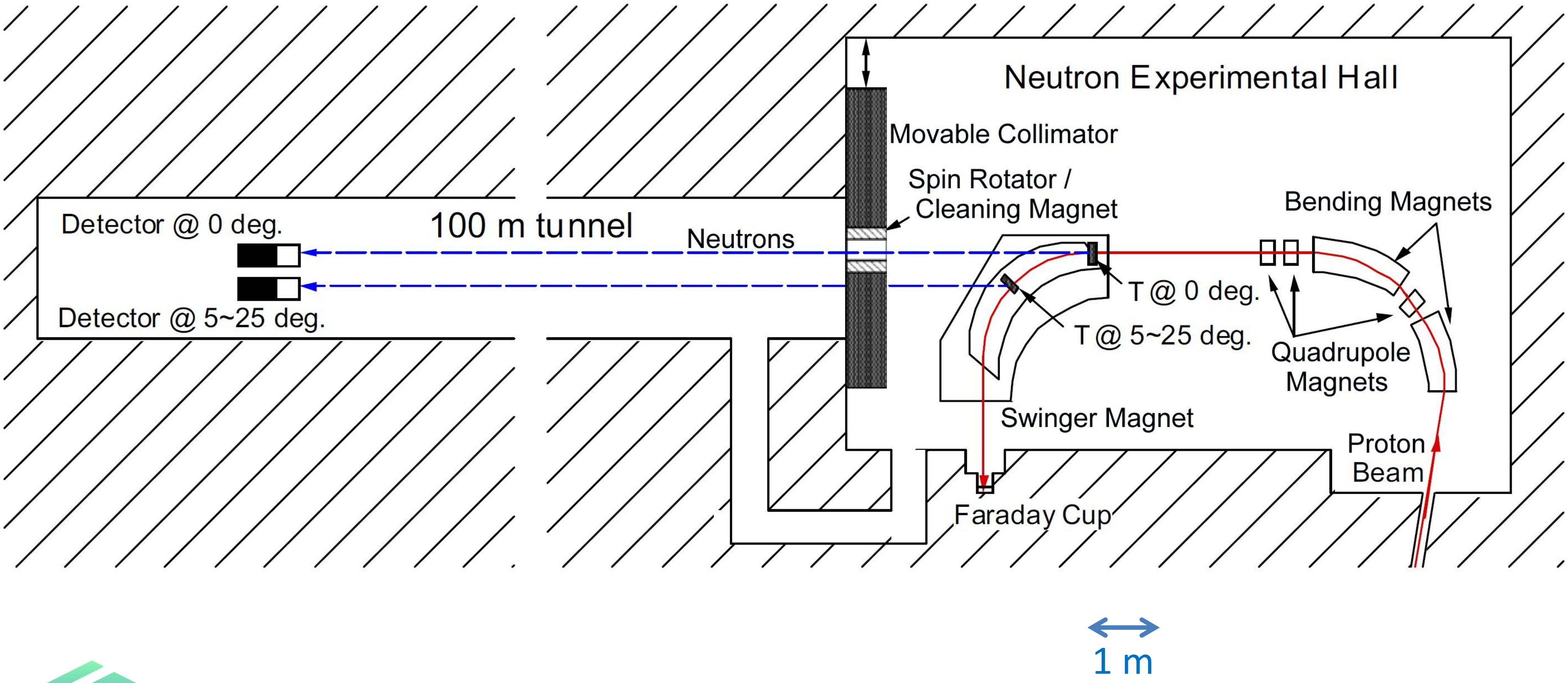
## Osaka University, Japan





# Research Center of Nuclear Physics

# Quasi-monochromatic neutron beamline “N0”




RCNP

DOI: 10.15669/pnst.4.657

*Progress in Nuclear Science and Technology*
Volume 4 (2014) pp. 657-660

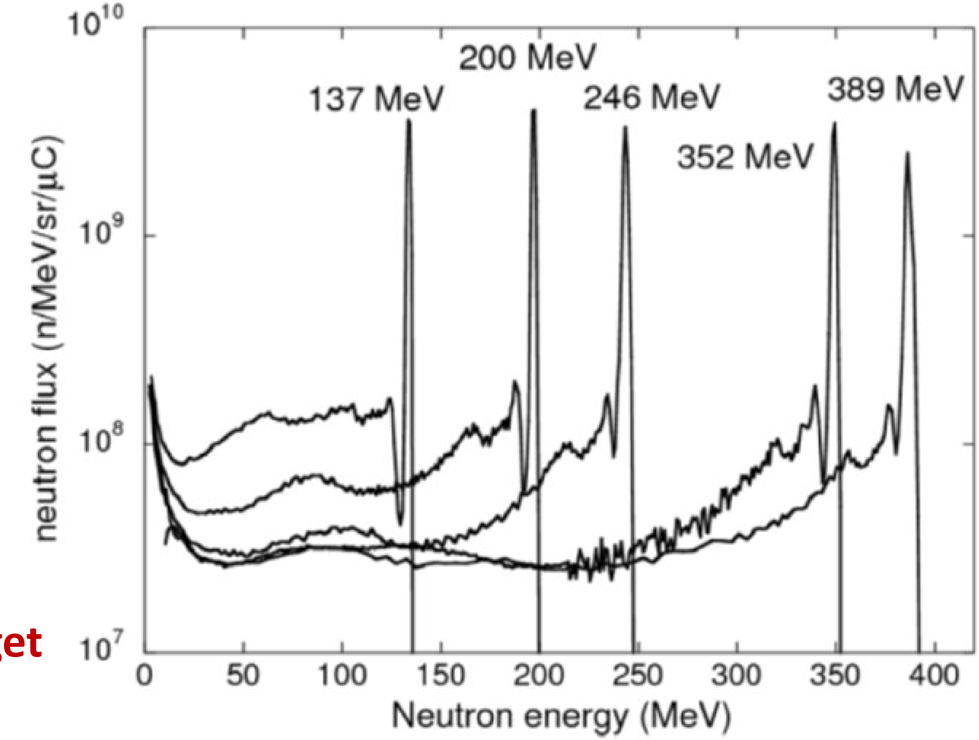
RCNP

ARTICLE

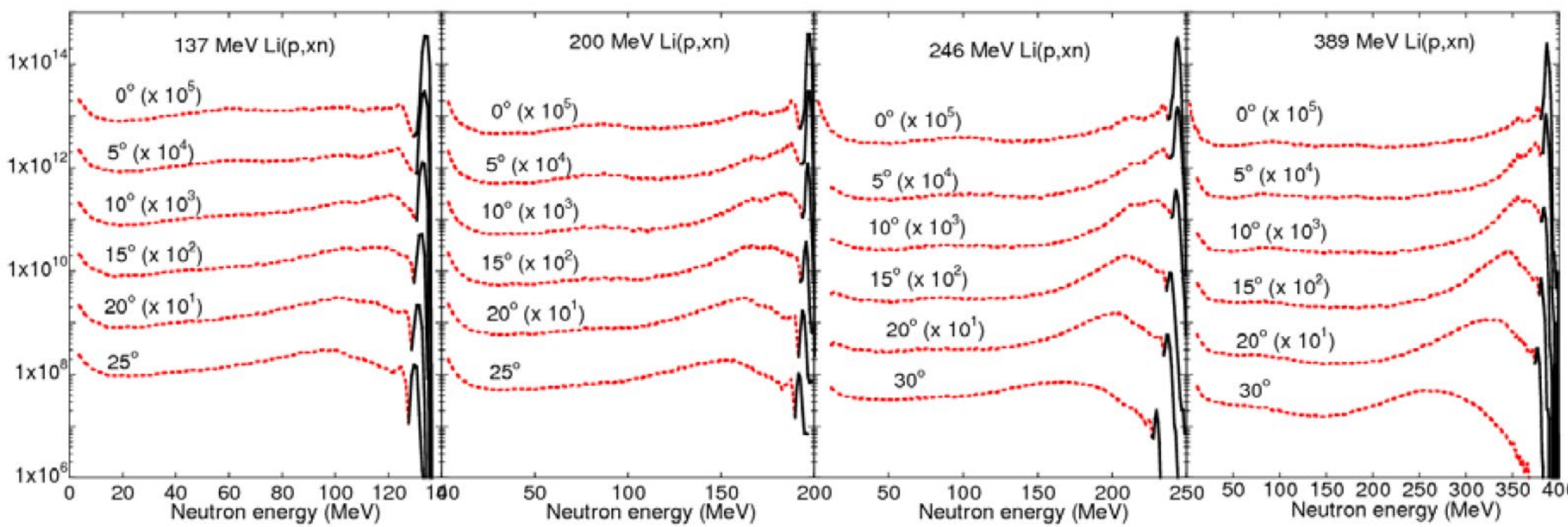
**Characterization of quasi-monoenergetic neutron source using 137, 200, 246 and 389 MeV $^{7}$Li(p,n) reactions**

Yosuke Iwamoto[a*], Masayuki Hagiwara[b], Hiroshi Iwase[b], Hiroshi Yashima[c], Daiki Satoh[a], Tetsuro Matsumoto[d], Akihiko Masuda[d], Christian Pioch[e], Vladimir Mares[e], Tatsushi Shima[f], Atsushi Tamii[f], Kichiji Hatanaka[f] and Takashi Nakamura[g]

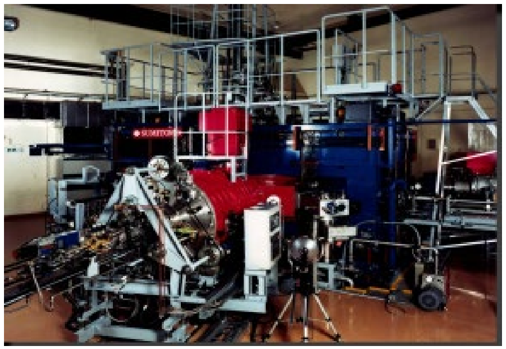
*[a]Japan Atomic Energy Agency, 2-4 Shirakata, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195, Japan; [b]High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba-shi, Ibarak-ken, 305-0801, Japan; [c]Research Reactor Institute, Kyoto University, 2-1010 Asashiro-nishi,Kumatori-cho, Sennan-gun, Osaka-hu, 590-0494, Japan; [d]National Institute of Advanced Industrial Science and Technology, 1-1-1 Higashi, Tsukuba-shi, Ibaraki-ken, 305-8561, Japan; [e]German Research Center for Environmental Health,Institute of Radiation Protection, Ingolstadter Landstr. 1, 85764 Neuherberg, Germany; [f]Research Center for Nuclear Physics,10-1 Mihogaoka, Ibaraki-shi, Osaka-hu. 567-0047, Japan; [g]Shimizu Corporation,4-17, Etchujima 3-Chome, Koto-ku, Tokyo-to, 135-8530, Japan*



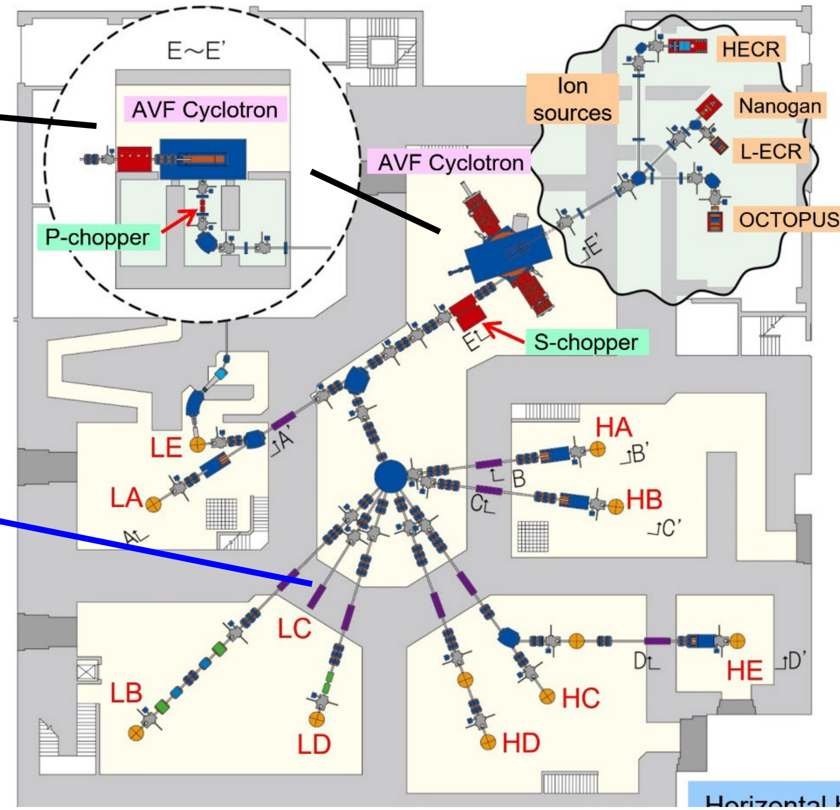

**Energy spectra of neutrons produced by proton beams irradiating a 10.0 mm Li target (measured with NE-213 at 100 m).**



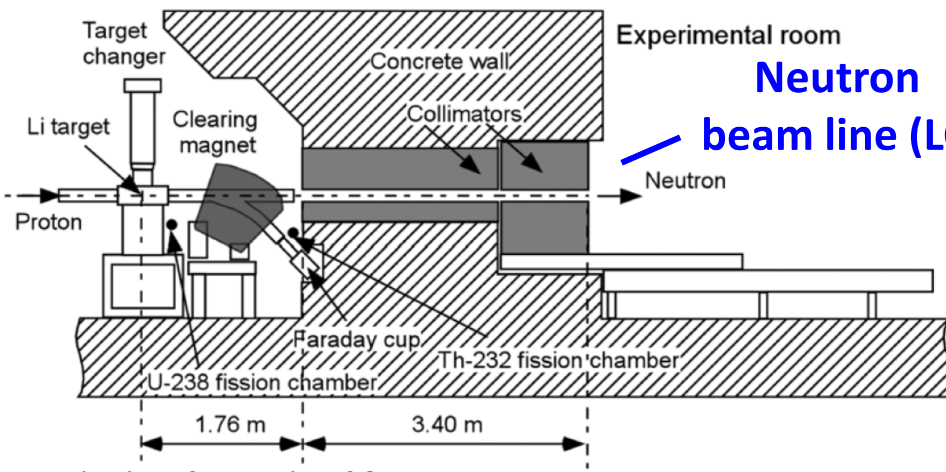
# Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) of the Takasaki Institute for Advanced Quantum Science (TIAQ), National Institutes for Quantum Science and Technology (QST).



AVF cyclotron
*k* = 110




Neutron beam line (LC)




Investigation of properties of the TIARA neutron beam facility of importance for calibration applications Get access

Y. Shikaze, Y. Tanimura, J. Saegusa, M. Tsutsumi, Y. Yamaguchi, Y. Uchita

*Radiation Protection Dosimetry*, Volume 126, Issue 1-4, August 2007, Pages 163–167, https://doi.org/10.1093/rpd/ncm035
**Published:** 22 May 2007

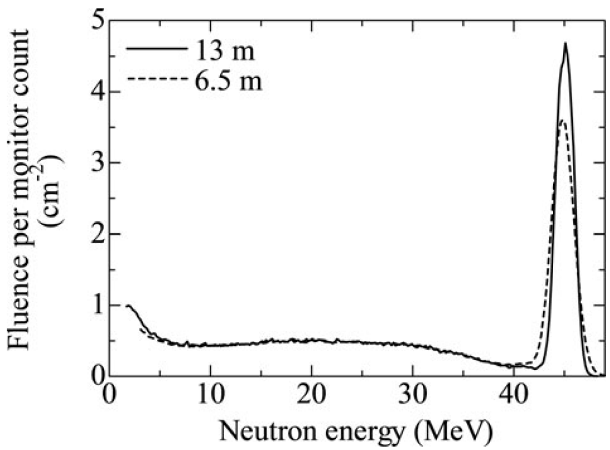
QST National Institutes for Quantum Science and Technology

# Takasaki Ion Accelerators for Advanced Radiation Application (TIARA)

## Energy spectra of neutrons produced by 50 MeV proton beam irradiating a 3.7 mm Li target (measured at 6.5 m and 13 m).

**Time-of-Flight**

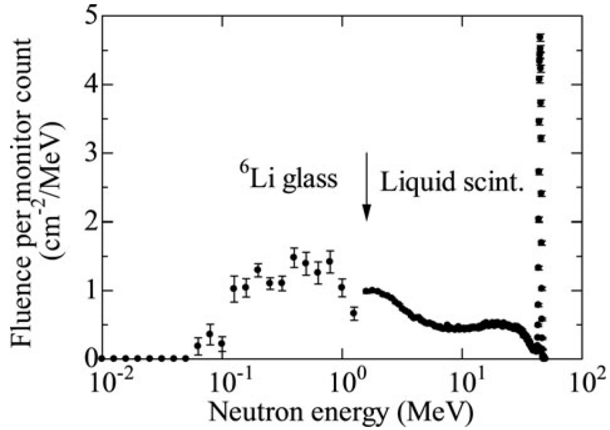
BC-501A



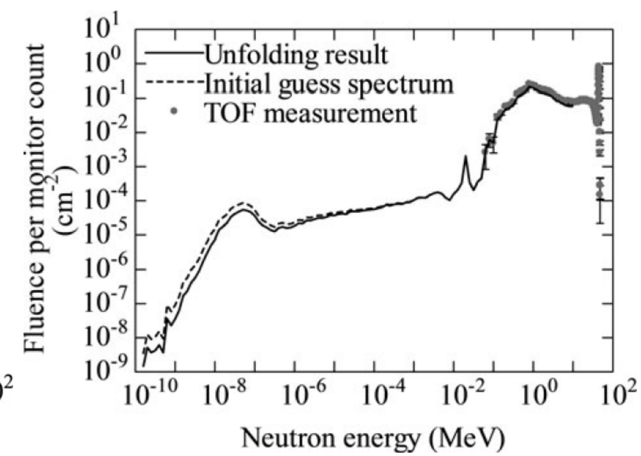

**Time-of-Flight**

BC-501A

$^6$Li glass GS20




**Bonner sphere unfolding**



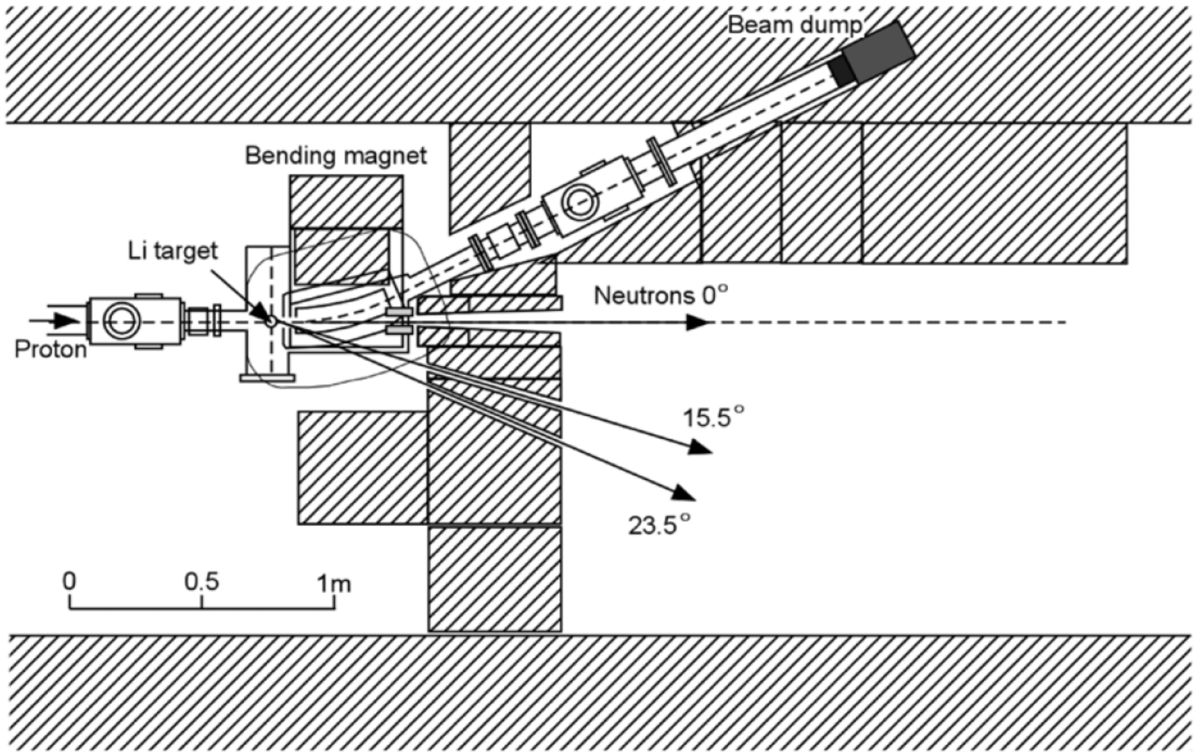

A. Masuda, et al., IEEE Trans. Nucl. Sci. 62, 1925-1300, 2015.

T. Matsumoto, et al., J. Nucl. Sci. Technol. 54, 529-538, 2017.

# Cyclotron and Radioisotope Center (CYRIC)
## Tohoku University, Sendai, Japan

AVF cyclotron

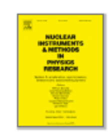
$k = 110$




ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 491, Issue 3, 1 October 2002, Pages 419-425



New fast-neutron time-of-flight facilities at CYRIC

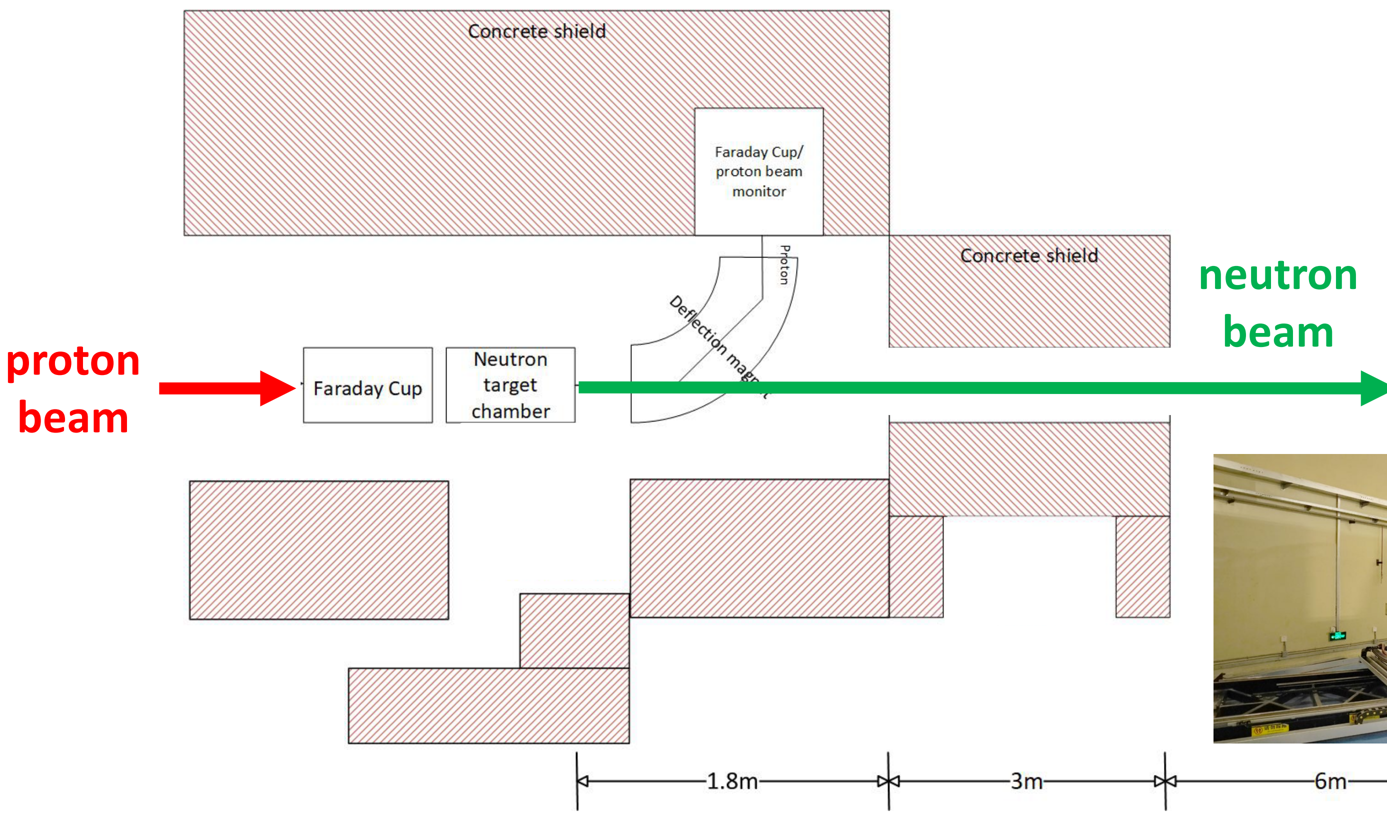
A Terakawa [a], H Suzuki [a], K Kumagai [a], Y Kikuchi [a], T Uekusa [a], T Uemori [a], H Fujisawa [a], N Sugimoto [a], K Itoh [a], M Baba [a], H Orihara [a], K Maeda [b]

# Fast neutron facility of the China Institute of Atomic Energy

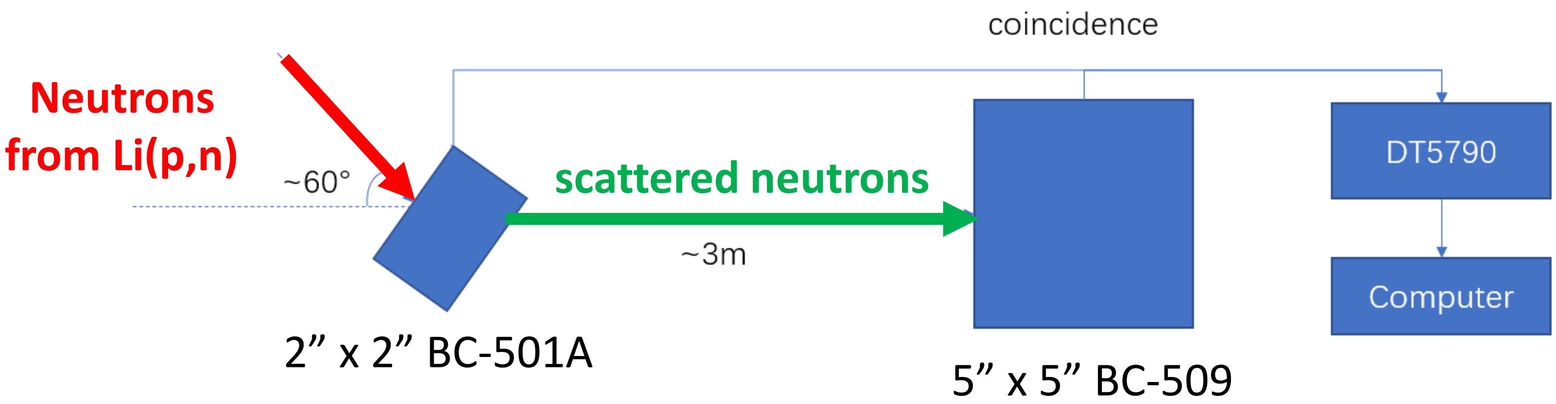
中核集团 CNNC 中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY

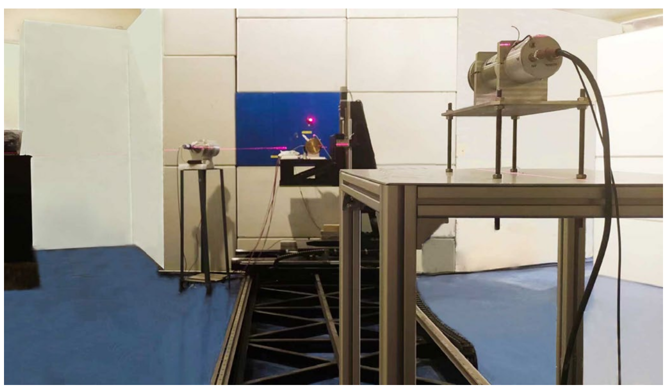
**Beijing, China**

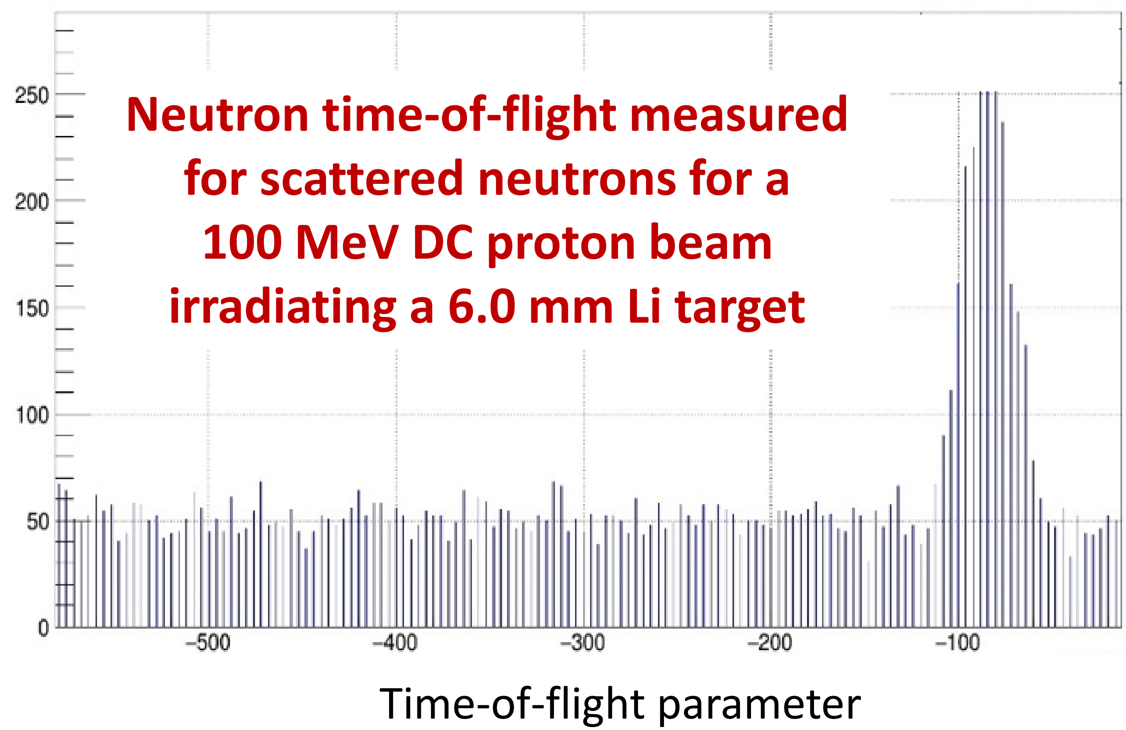
- CYCIAE-100 high current cyclotron (230 μA)
- 75 – 100 MeV protons DC




# Fast neutron facility of the China Institute of Atomic Energy



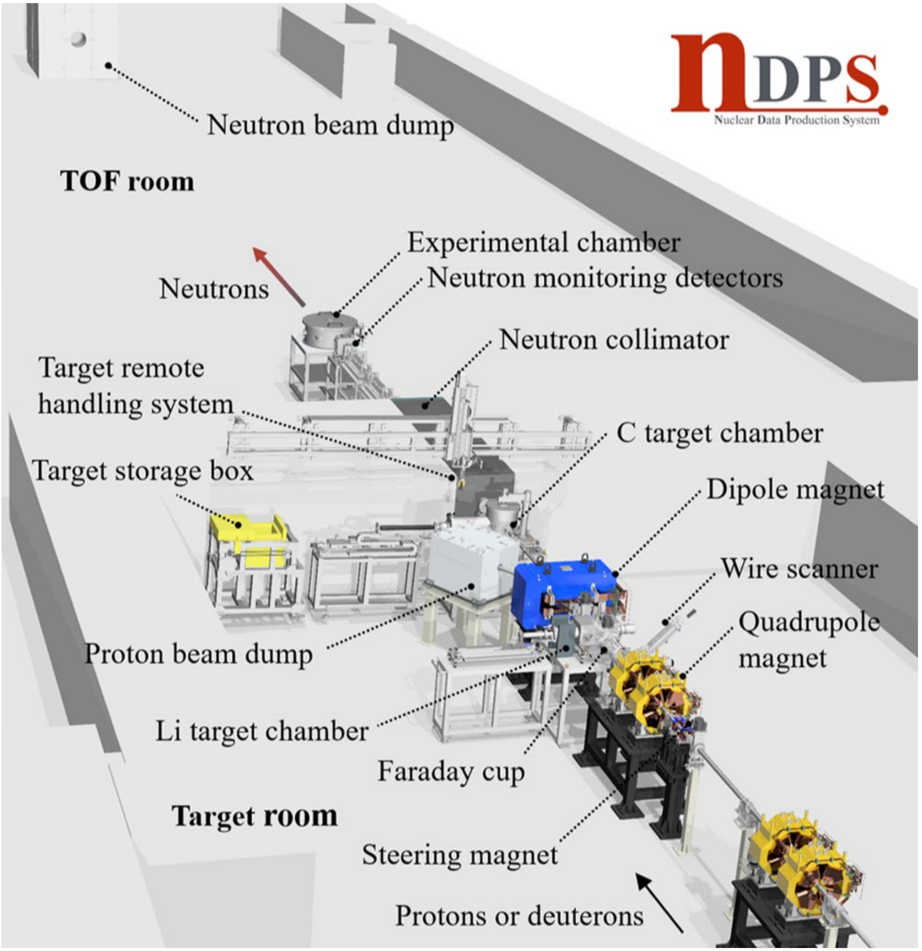






中国原子能科学研究院
中核集团 CNNC
CHINA INSTITUTE OF ATOMIC ENERGY

# Nuclear data production system (NDPS)
# RAON, Korea

Institute for Rare Isotope Science




*Transactions of the Korean Nuclear Society Spring Meeting*
*Jeju, Korea, May 22-23, 2025*

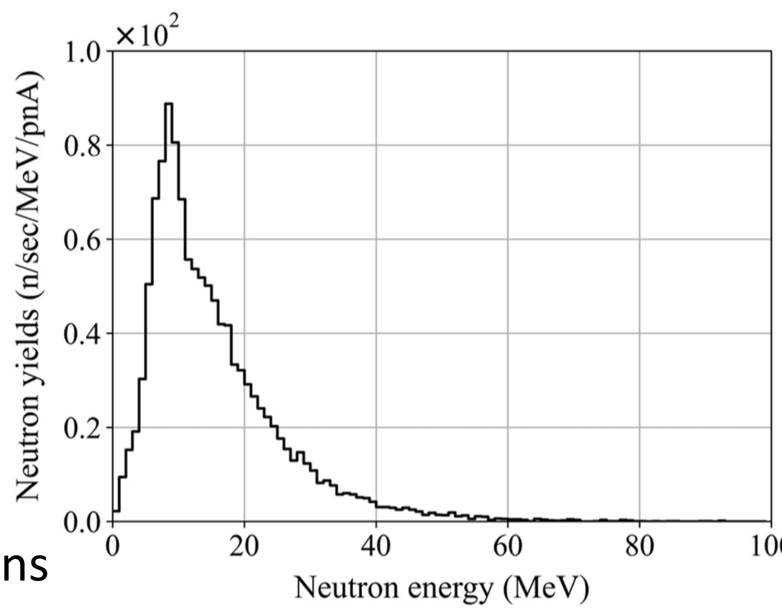
**May 2025**

**A Fast Neutron Experimental System at RAON**

Cheolmin Ham[a*], CheongSoo Lee[a], Geonhee Oh[a], Kwang-Bok Lee[a], Donghyun Kwak[a], Jaesung Kim[a, b], Seong Jae Pyeun[a], Sangjin Lee[a], EunHee Kim[a], Changwook Son[a], Dong Geon Kim[a], Minsik Kwag[a], Jae Cheon Kim[a], Mi Jung Kim[a], Young-Ouk Lee[a, c], Do Gyun Kim[a], Jinho Lee[a], and Kyoungho Tshoo[a]

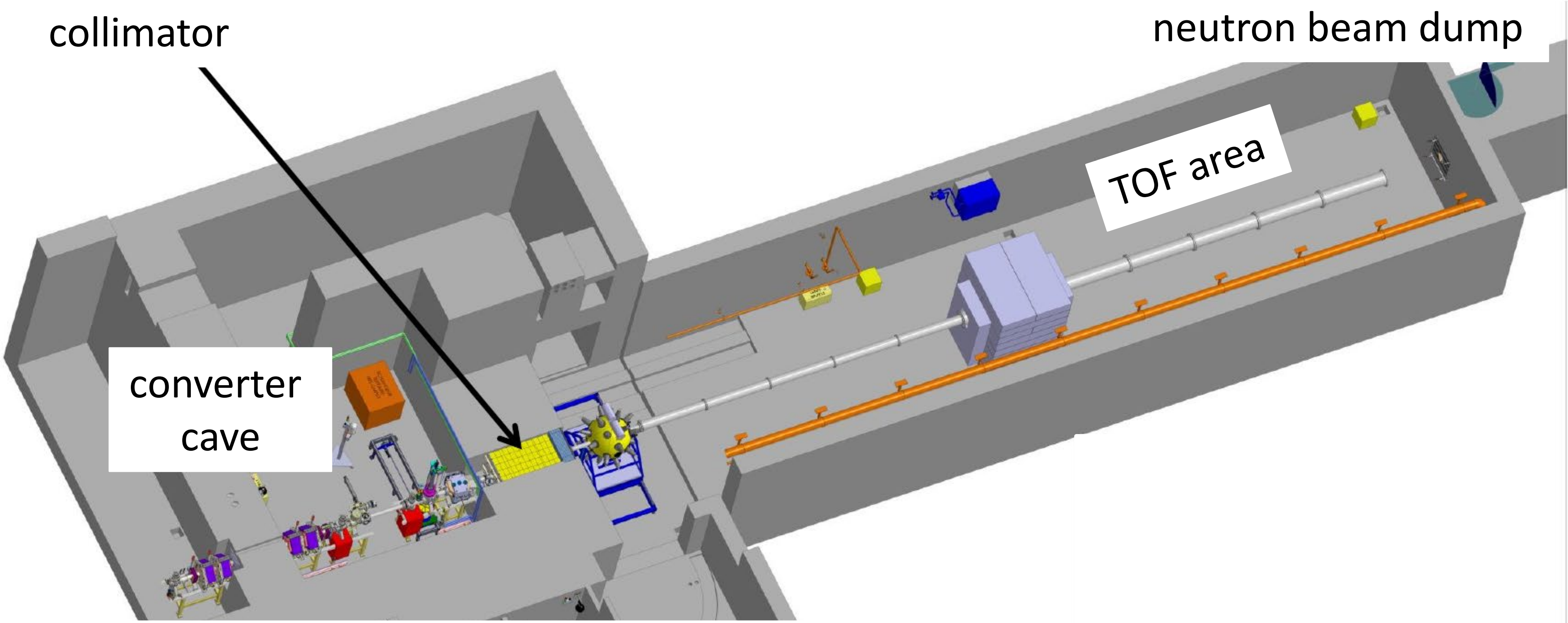
[a]*Institute for Rare Isotope Science, Institute for Basic Science, Daejeon 34000, Republic of Korea*
[b]*Department of Nuclear Engineering, Seoul National University, Seoul 08826, Republic of Korea*
[c]*Nuclear Data Center, Korea Atomic Energy Research Institute, Daejeon 34057, Republic of Korea*
[*]*Corresponding author: cmham@ibs.re.kr*

**Energy spectra of neutrons produced by 16 MeV/u $^{40}Ar$ on 28 mm C target (measured at 4.8 m)**

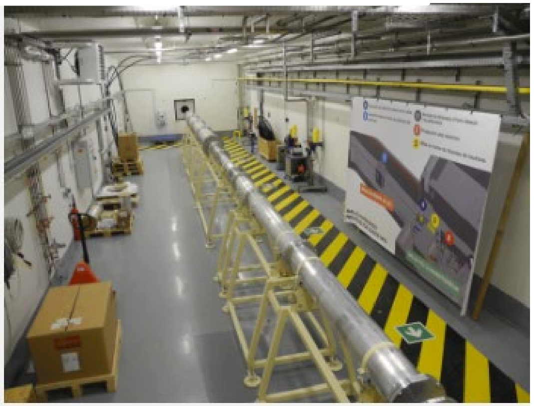



- Superconducting linear accelerator 3 (SCL3)
- Quasi-monoenergetic and broad energy neutrons up to 83 MeV (p+Li) or 98 MeV (d+Be).

# Neutrons For Science Facility




Target station



ToF hall

- Superconducting LINAC
- Beam at 0°
- Good collimation
- TOF over 28 m

# Neutrons For Science Facility of GANIL/SPIRAL2

Eur. Phys. J. A (2021) 57:257
https://doi.org/10.1140/epja/s10050-021-00565-x

THE EUROPEAN PHYSICAL JOURNAL A

Letter to the Editor

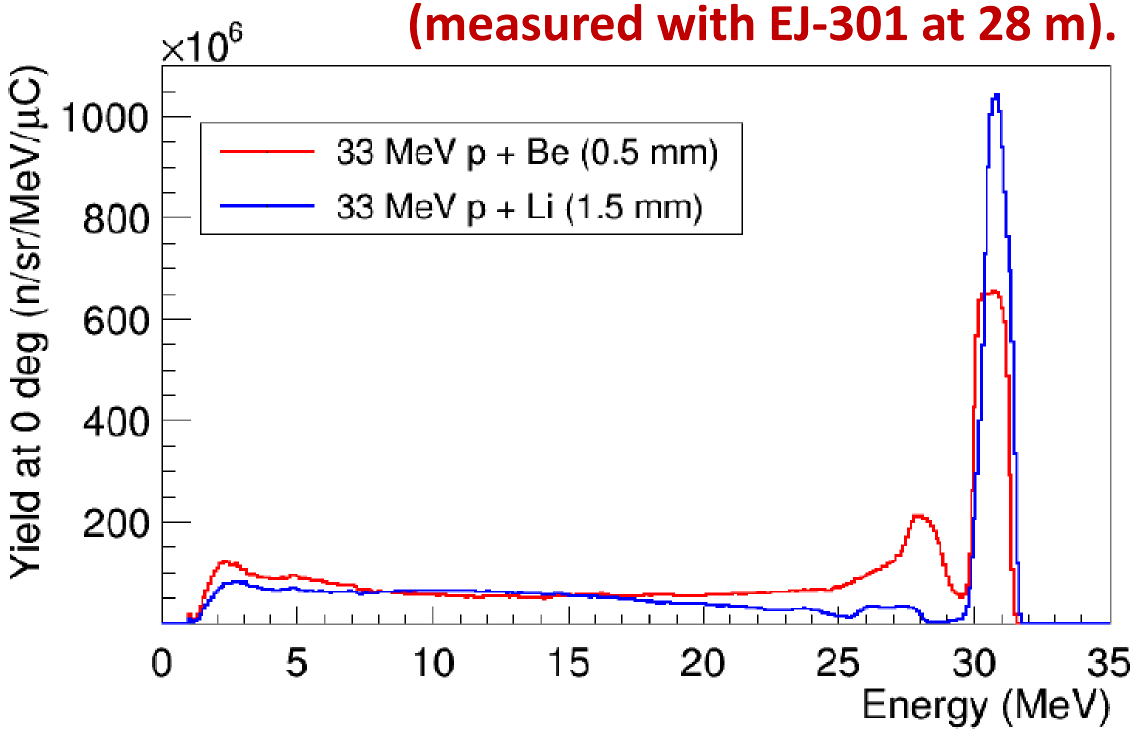
**First beams at neutrons for science**

X. Ledoux[1,a], J. C. Foy[1], J. E. Ducret[1], A. M. Frelin[1], D. Ramos[1], J. Mrazek[2], E. Simeckova[2], R. Behal[2], L. Caceres[1], V. Glagolev[2], B. Jacquot[1], A. Lemasson[1], J. Pancin[1], J. Piot[1], C. Stodel[1], M. Vandebrouck[3]

[1] Grand Accélérateur National d'Ions Lourds, CEA/DRF-CNRS/IN2P3, B.P. 55027, 14076 Caen, France
[2] Nuclear Physics Institute of the Czech Academy of Sciences, 250 68 Řež, Czech Republic
[3] IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

- Superconducting LINAC
- Time-of-flight hall: 28 m
- Neutron beams 1-40 MeV
- High flux

**Energy spectra of neutrons produced by 33 MeV proton beams irradiating thin Li and Be targets (measured with EJ-301 at 28 m).**



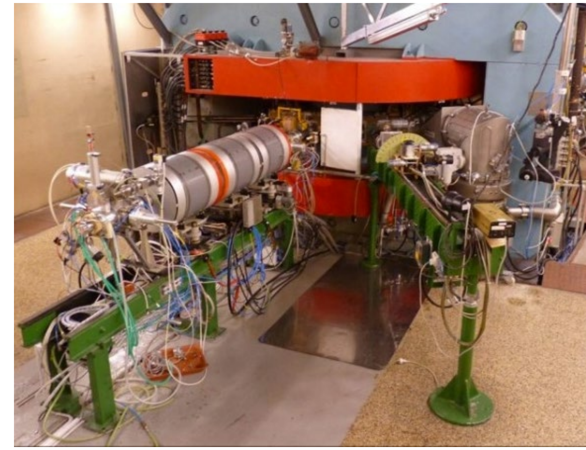
# Fast neutron facility at CAS Nuclear Physics Institute

NUCLEAR PHYSICS INSTITUTE CAS
public research institution

The Czech Academy of Sciences

Řež, Czech Republic

- Isochronous cyclotron U-120M
- Proton beams 1-37 MeV



**Energy spectrum of neutrons produced by 32.5 MeV proton beam irradiating a 2 mm Li target (measured with NE-213 at 4.5 m).**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Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics A 953 (2016) 139–157

NUCLEAR PHYSICS A

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Au, Bi, Co and Nb cross-section measured by quasimonoenergetic neutrons from p + $^7$Li reaction in the energy range of 18–36 MeV


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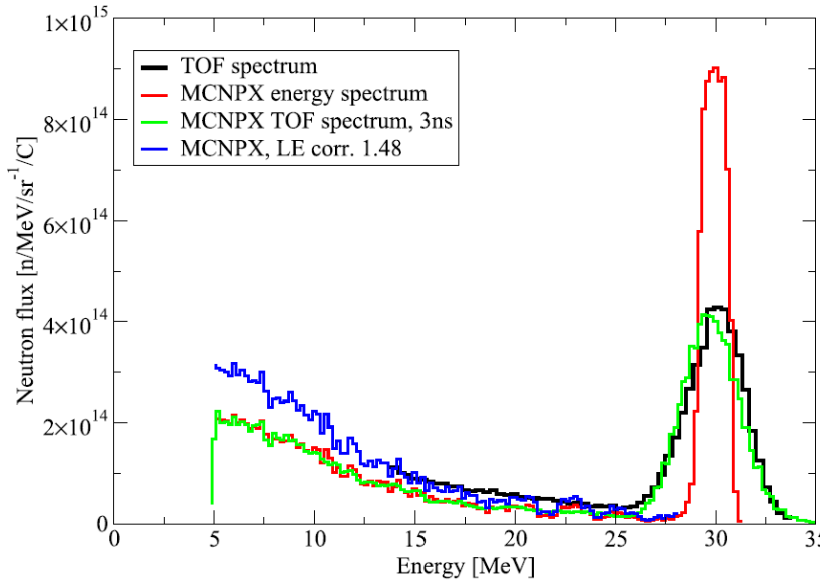
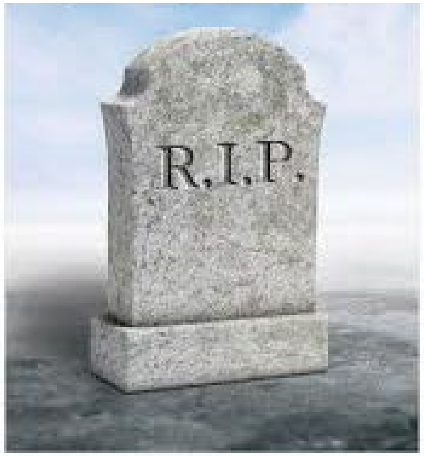


## Three important high energy neutron facilities closed over last decades:

- Cyclotron Research Centre,
  Catholic University of Louvain-la-Neuve, Belgium

- The Svedburg Laboratory,
  Uppsala University, Sweden

- Indiana University Cyclotron Facility,
  Indiana University, USA



# Global menu
# Quasi-monoenergetic HE neutron fields

Max.

| Facility | | | $E_p$ (MeV) | Pulsing | Neutron beam angle | ToF path (m) |
|---|---|---|---|---|---|---|
| | | | | | | |
| iThemba LABS | NRF National Research Foundation iThemba LABS Laboratory for Accelerator Based Sciences | South Africa | 35-200 | ns | 0 and 16 | 10 |
| RCNP | RCNP | Japan | 100-400 | ns | 0 to 30 | 100 |
| TIARA | QST | Japan | 40-90 | ns | 0 | 13 |
| CYRIC | TOHOKU UNIVERSITY | Japan | 20-90 | ns | 0 | ? |
| CIAE | 中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY 中核集团 CNNC | China | 75-100 | DC | 0 | (3) |
| IRIS | IRIS Institute for Rare Isotope Science | Korea | 83 | ns | 0 | 50 |
| NFS | GANIL | France | 20-33 | ns | 0 | 28 |
| NPI | NUCLEAR PHYSICS INSTITUTE CAS public research institution | Czech Rep | 18-36 | ns | 0 | 5 |
| Future facilities ? | | | | | | |

## Do we need (quasi)monoenergetic fields (as well as broad energy fields)?

… metrology generally (ToF)
… metrology for response functions (ToF)
… detector response (no ToF) *
… passive irradiation … subtraction effect *

* … ToF not required for “quasi” => quasi

# Wish list

- **Quasi-monoenergetic neutron fields over a wide energy range (offering peak energies from about 20 MeV to several hundred MeV);**
- **Well-characterized and reproducible neutron energy distributions; and**
- **Low, well-characterized background.**

- A stable short-pulsed proton beam of sufficient intensity;
- Adjustable time between subsequent proton pulses (pulse selection/beam kicker);
- Real time monitoring of proton beam focus by accelerator operators;
- Good target control with well shielded neutron production area;
- Excellent proton beam removal in dump, with good beam charge measurement;
- Well characterised neutron collimation, with sufficiently narrow (and wide) profile;
- Sufficiently large experimental hall designed for low scattering background;
- Sufficiently long Time-of-Flight path;
- Several neutron beam measurement angles (e.g. 0° and 20°);
- Good vault infrastructure; patch panels; clean earth; etc.
- Reference instrumentation for neutron beam (spectral) fluence measurement ($u < 5\%$);
- Well characterised and stable beam monitors.

Accessibility (e.g. PAC); general technical support; experience …

# Final thoughts

… that there is much stronger **international coordination and cooperation** … including a "community of facilities".

… that **ISO 17025 (compatible) guidelines** are drafted to guide the evolution of existing and new facilities … covering …
charged particle beam production, focusing, stability and monitoring;
neutron production; collimation; backgrounds; neutron beam size and profile; and
primary and secondary fluence measurement including traceability, and reporting.

… that plans are designed to guide **key comparison studies** between participating NMI facilities … coordinated by CCRI … :
… using the same reference instrument in different facilities at the same energy;
… and using many different instruments at one (or two) facilities at two energies.

… including a project to design the uncertainty budget for: