Development of Cyclotron for Neutron Radiography in KOREA

CHAI, Jong-Seo

Presented by Mitra Ghergherehchi

Sungkyunkwan University
Contents

1. Neutron Radiography with Cyclotrons
2. Cyclotron Design for Neutron Radiography
Characteristics of Neutron Radiography

• Although the interaction of electrons at ion and x-ray and gamma ray increases as atomic number goes higher, neutron has no such tendency so that cross section of the reaction becomes intrinsic property.

• Light elements has more contrast for neutron than x-ray and gamma ray. Neutron has relatively higher transmission ability for massive elements.

• Neutron radiography can be used complementally for non-destructive test with x-ray and gamma radiography.
# Neutron Source Characteristics

<table>
<thead>
<tr>
<th>Source</th>
<th>Flux capabilities ( n.cm^{-2}.s^{-1} )</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>( 10^{10}-10^{15} )</td>
<td>High flux</td>
<td>High cost, complex</td>
</tr>
<tr>
<td>Accelerator</td>
<td>( 10^{7}-10^{10} )</td>
<td>Good flux, Portability</td>
<td>Target life - poor moderately complex to operation</td>
</tr>
<tr>
<td>Isotopic</td>
<td>( 10^{5}-10^{9} )</td>
<td>Small size, Easy operation, portability</td>
<td>Low flux level, decay of intensity, continuous output</td>
</tr>
</tbody>
</table>
Various Reactions used for N-target

\[ ^2H(d,n)^3He, \, Q = 3.269 \quad 3H(d,n)4He, \, Q = 17.589 \]

- \[ D+T\rightarrow n+^4He \quad E_n=14.2\text{MeV} \, \text{(n; isotropically emitted)} \]
- \[ D+D\rightarrow n+^3He \quad E_n=2.5 \text{ MeV} \, \text{(n: slightly peaked in the forward direction)} \]
  He: emitted in the exact opposite direction.

\[ ^9Be(p,n)^9B, \, Q = -1.851 \quad ^7Li(p,n)^7Be, \, Q = -1.644 \]

**Accelerator based neutron sources**

<table>
<thead>
<tr>
<th>reaction</th>
<th>Neutron E(MeV)</th>
<th>Typical fast neutron output/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>T(d,n)</td>
<td>2 to 4</td>
<td>1 to 4x10^{11}</td>
</tr>
<tr>
<td>Be(d,n)</td>
<td>1.6</td>
<td>1x10^{10}</td>
</tr>
<tr>
<td>Be(γ,n)</td>
<td>1.4</td>
<td>2x10^{11}</td>
</tr>
</tbody>
</table>
Cross Section as Function of Proton Beam Energy and Measurement Angles

- $E_p = 8-16\text{MeV}$
- $\Theta_{\text{c.m.}} = 0-180^\circ$

- $E_p$ increase $\rightarrow$ neutron yields rise at $0^\circ$
Zero-degree Excitation Function

$^9\text{Be}(p,n_0)^9\text{B}$

$E_X$ (MeV)

$\sigma_{c.m.}(0^\circ)$ (mb/sr)

$E_p$ (MeV)

Present $\sigma(\theta)$.

Soji

Bouer et al.

Walker et al.

McNaughton et al.

Present $\sigma(E)$
$^9$Be(p,n)$^9$B Reaction

- **Triangle Univ. Nuclear Lab**, Duke Station, USA
- **FN tandem Van de Graaff** accelerator: $E_p = 8$ to $16$ MeV
- **Be target**: 0.25 mm Stainless steel cylinder wall
  - 0.5 mm tantalum beam stop (n trans: 98%)
  - $^9$Be foil: thickness 4.36 mg/cm$^2$
    - energy loss: 200keV at 8MeV to 110keV at 16MeV
- **Detector**: a pair of NE-218 detector (diameter: 8.9, 12.7cm)
- **TOF**: max. flight path (3.76, 5.67 m)
- **Time resolution**: 2 ns
- **Beam current**: 80-120nA
- **Pulse-height discrimination**: proton recoil energy of about 1.9MeV
- **Detector efficiency calibration**: $^2$H(d,n)$^3$He cross section

TOF Spectrum of n at $^9\text{Be}(p,n)^9\text{B}$ Reaction

- Identification of the excite state structure of the residual nucleus by TOF spectrum
Cyclotron used for NR

MC-50 Cyclotron

Switching Magnet

Beamline for Gamma Exp.

proton beam (35MeV)

Be9 Target

Bending Magnet (70 degree)

Aluminum Absorber

Neutron/Gamma

Beam Dump

Gantry

Treatment Room

Detector

RI Production Beamline

SUNGKYUNKWAN UNIVERSITY
Accelerator & Medical Engineering Laboratory
Schematic Diagram of Neutron Radiography System

- Cyclotron
- Proton Beam
- Be-Target
- Object
- Scintillation Converter
- Monitor
- Image Processor
- CCD Camera
- Video Recorder
- Image Processor
- Floppy Disk
Comparison of X-Radiography and Neutron Radiography

Neutron

X-ray (120keV)
Li-ion Battery Imaging by Neutron Radiography
Image of Lead-Shielded Battery by Neutron Radiography
Comparison of X-ray and Neutron Radiography for Electrical Drill

X-ray

neutron
NR experimental facility at KAERI
KIRAMS 30 – General Specifications

Type of Accelerated Ions: Negative Hydrogen
Extraction method: Stripper carbon foil
Beam Energy (proton): 15 ~ 30 MeV
Beam Current (proton): Guaranteed 300 uA
No. of Beam lines: 4
Dual beam: available
Cyclotron Design
SKKU Cyclotron for NR

• High intensity H⁻ cyclotron for neutron generator
• Application: Neutron Radiography
• Accelerating beam: negative hydrogen ion
• Extracting beam to target: proton
• Energy of the extracting beam: 4 MeV
  - beam energy required
    ~ 2.5 MeV for Li target
    ~ 4 MeV for Be target
• Beam current: up to 2 mA
# General Specification

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle</td>
<td>H⁻</td>
</tr>
<tr>
<td>Extraction energy</td>
<td>4 MeV</td>
</tr>
<tr>
<td>Ion source</td>
<td>20 mA H⁻ multicusp</td>
</tr>
<tr>
<td>Injection energy</td>
<td>40 keV</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>2 mA</td>
</tr>
<tr>
<td>Target</td>
<td>Be-Li hybrid</td>
</tr>
</tbody>
</table>

## Magnet

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sectors</td>
<td>4</td>
</tr>
<tr>
<td>$B_0$</td>
<td>0.8 T</td>
</tr>
<tr>
<td>Extraction radius</td>
<td>39.7 cm</td>
</tr>
<tr>
<td>Pole radius</td>
<td>45 cm</td>
</tr>
<tr>
<td>Hill/Valley gap</td>
<td>4 / 52 cm</td>
</tr>
<tr>
<td>Hill angle</td>
<td>&gt; 40°</td>
</tr>
<tr>
<td>Coil dimension</td>
<td>$7_{dpc} \times 10$ turns</td>
</tr>
<tr>
<td>Dee angle</td>
<td>43°</td>
</tr>
<tr>
<td>Dee voltage</td>
<td>50 kV</td>
</tr>
<tr>
<td>Coupling</td>
<td>Capacitive</td>
</tr>
<tr>
<td>Power</td>
<td>&lt;50 kW</td>
</tr>
<tr>
<td>Power</td>
<td>~ 8 kW</td>
</tr>
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</table>

## RF

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonic number</td>
<td>4</td>
</tr>
<tr>
<td>RF frequency</td>
<td>48.83 MHz</td>
</tr>
<tr>
<td>Number of dees</td>
<td>2</td>
</tr>
<tr>
<td>Dee angle</td>
<td>43°</td>
</tr>
<tr>
<td>Dee voltage</td>
<td>50 kV</td>
</tr>
<tr>
<td>Coupling</td>
<td>Capacitive</td>
</tr>
<tr>
<td>Power</td>
<td>&lt;50 kW</td>
</tr>
</tbody>
</table>
Magnet System

Prototypes of Magnet and Coils

- Pancake type
- 4 Sector-magnet with deep valleys
- 4 holes for vacuum pump & RF cavity
- 1 central hole for axial injection
Calculated magnetic field distribution and the equilibrium orbits (EO) when the energies are 1, 2, 3, and 4MeV.
RF System

- Vertical stem
- Quarter wavelength resonators
- Harmonic number: 4
- 2 dees at the valleys
- RF frequency: 48.83 MHz
- The capacitive coupling method

RF dee and cavity
The electric field distribution between electrodes (dee and liner). The arrows represent the strength and the direction of the electric field. Q value is about 8600.
Injection System

• The external beam transport from the ion source up to the top of the magnet yoke
• The beam is bent into the median plane of the cyclotron by the inflector

Spiral Inflector simulation results
External Ion Source

- Intensities of proton beam are limited in extraction
- The negative hydrogen ion is chosen as an accelerating ion beam
- RF driven, multi-cusp ion source for negative hydrogen ion beam
- The source will give over 5mA at a voltage of about 6kV

Schematic of RF ion source
Extraction System

- H- ion beam is extracted by the carbon stripper foil
- The extracting beam energy can be changed by the position of stripper foil

Extraction System of SKKUCY-4
Vacuum System

• For low energy, high intensity negative ion beam, it is very important to have a good vacuum.

• 2 holes in the magnet for vacuum pumps and 2 holes for the symmetry of the magnetic field

• 2 diffusion pump pump with mechanical pumps

Bottom view of the magnet
Cyclotron Viewing

- Picture of the cyclotron chamber open.
  The estimated mass of the machine is about 9.1 ton.

- Drawings of the magnet and RF systems assembled.
Solid Lithium Target
Material properties of Lithium

- Atomic Number : 3
- Atomic weight : 6.941
- Melting point : 180.54 °C (=453.54 K)
- Boiling point : 1350 °C  (=1623 K)

Chemical reaction

i) $4\text{Li} + \text{O}_2 \rightarrow 2\text{Li}_2\text{O}$

ii) $6\text{Li} + \text{N}_2 \rightarrow 2\text{Li}_3\text{N}$

iii) $2\text{Li} + 2\text{H}_2\text{O} \rightarrow 2\text{LiOH} + \text{H}_2$

iv) $\text{Li} + 4\text{Cu} \rightarrow \text{Cu}_4\text{Li}$
Target Object

- High irradiation currents (exceed 1 mA)

The solving methods

- Minimize unit energy
  - Increase irradiation area
  - Reduce target thickness

- Improve cooling efficiency
  - Mass cooling flow
  - Low temperature as possible
Neutron Target Design

- Target material: Li
- Target thickness: 100 μm
- Target base: Cu
- Angle of inclination: 30 degree
- Energy absorption length: 200 μm
- Energy to Target: 1.7986 MeV

Incident energy: 2.5 MeV
Final energy: 0.7014 MeV

Beam type: Proton
- Target size: 30 x 64 mm (ellipse)
- Irradiation area: 14.13 cm²
- Cooling flow: 40 L/min (water)

<table>
<thead>
<tr>
<th>Incident Energy</th>
<th>Absorption length</th>
<th>2.8MeV</th>
<th>2.5MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 μm</td>
<td>1.4734</td>
<td>1.7986</td>
<td></td>
</tr>
<tr>
<td>300 μm</td>
<td>stopped</td>
<td>stopped</td>
<td></td>
</tr>
</tbody>
</table>
Analysis

- Software: FLUENT
- Condition
  - 1.7 MeV, 1 mA on Li
  - Angle: 30°
  - Thickness: 100μm
  - Flow rate: 40 L/min, 15 °C
- Result
  - Maximum Temperature: 325 K (= 52 °C)
Needs for Real Test

- High current cyclotron
- Large size beam shape or warbling system
- Mass cooling flow chiller system
- Vacuum furnace

Recommend for high current Li target

- Angle of inclination : 20 degree
- Energy absorption length : 292 μm using 100 μm Li, Beam stopped
- Almost same power condition as analysis
# Summary

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>~ 2 mA of 4 MeV proton</td>
</tr>
<tr>
<td>Ion Source</td>
<td>External multi-cusp H⁻ ion source</td>
</tr>
<tr>
<td>Injection</td>
<td>Axial Injection using inflector</td>
</tr>
<tr>
<td>Magnet Sectors</td>
<td>4</td>
</tr>
<tr>
<td>Magnet Pole Diameter</td>
<td>~ 60 cm</td>
</tr>
<tr>
<td>Number of Dees</td>
<td>2</td>
</tr>
<tr>
<td>Harmonic Number</td>
<td>4</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>~ 48.83 MHz</td>
</tr>
<tr>
<td>Extraction Method</td>
<td>Charge Exchange Carbon Stripper Foil</td>
</tr>
</tbody>
</table>
Conclusion

1. Cyclotron is one of the compact strong candidate for neutron source.
2. With superconducting magnet cyclotron can be portable use.
3. Cyclotron is economical and reliable accelerator for neutron generation.
Thank you for Your Attention