Development of Cyclotron for Neutron Radiography in KOREA

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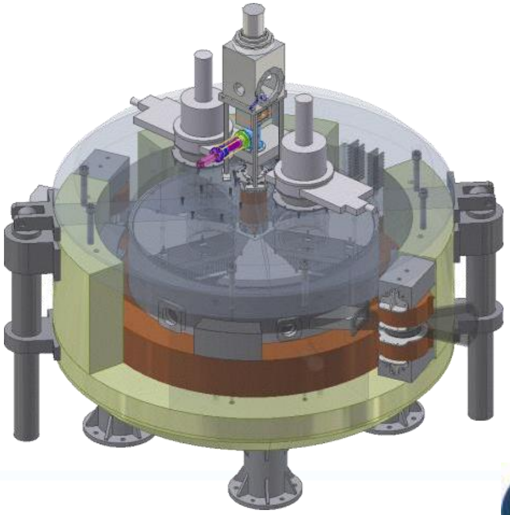


Characteristics of Neutron Radiography

- **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

Source	Flux capabilities $n.cm^{-2}.s^{-1}$	Advantages	Disadvantages
Reactor	10^{10}-10^{15}	High flux	High cost, complex
Accelerator	10^{7}-10^{10}	Good flux, Portability	Target life - poor moderately complex to operation
Isotopic	10^{5}-10^{9}	Small size, Easy operation, portability	Low flux level, decay of intensity, continuous output

Various Reactions used for N-target

$^{2}H(d,n)^{3}He$, Q= 3.269 **3H(d,n)4He, Q= 17.589**

D+T→n+^{4}He E_n=14.2MeV (n; isotropically emitted)

D+D→n+^{3}He E_n=2.5 MeV (n: slightly peaked in the forward direction)

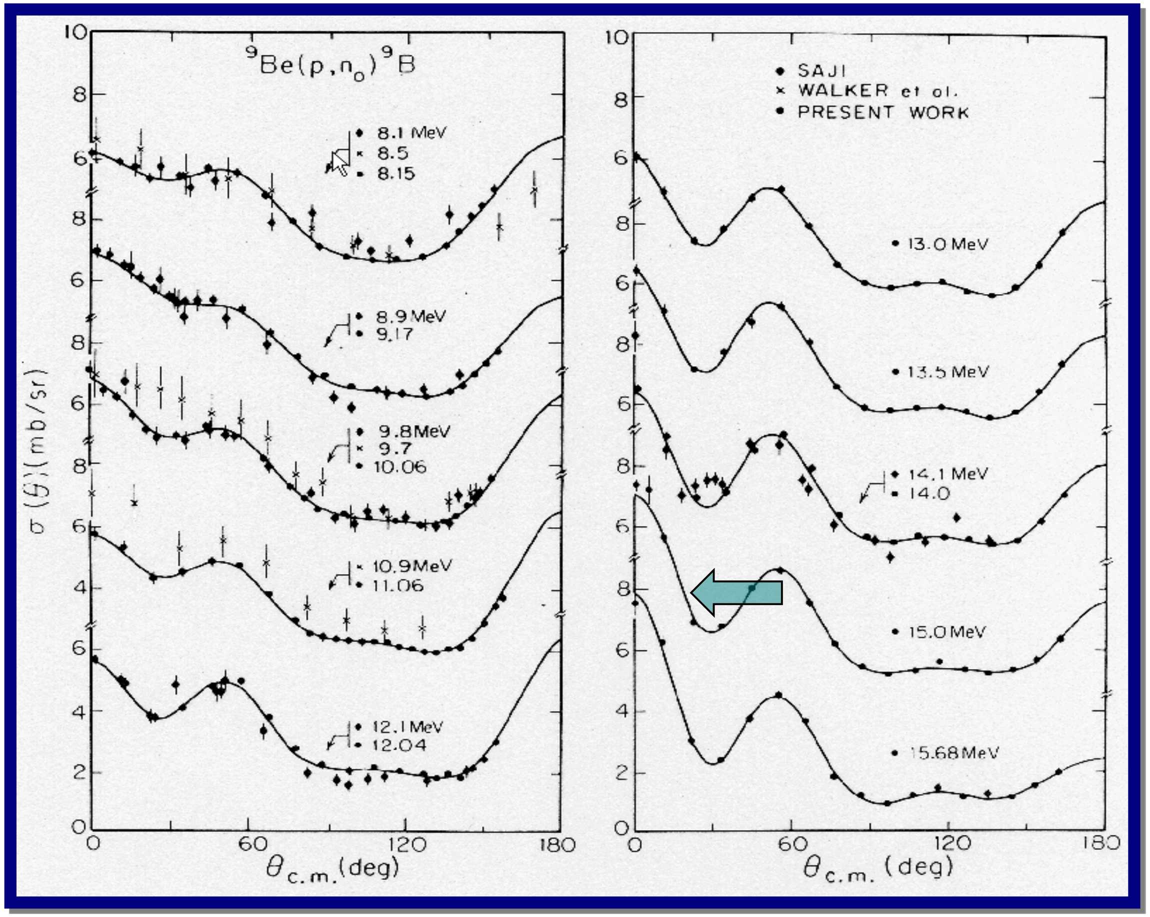
He: emitted in the exact opposite direction.

$^{9}Be(p,n)^{9}B$, Q= -1.851 **$^{7}Li(p,n)^{7}Be$, Q= -1.644**

Accelerator based neutron sources

reaction	Neutron E(MeV)	Typical fast neutron output/s
T(d,n)	2 to 4	1 to 4×10^{11}
Be(d,n)	1.6	1×10^{10}
Be(γ,n)	1.4	2×10^{11}

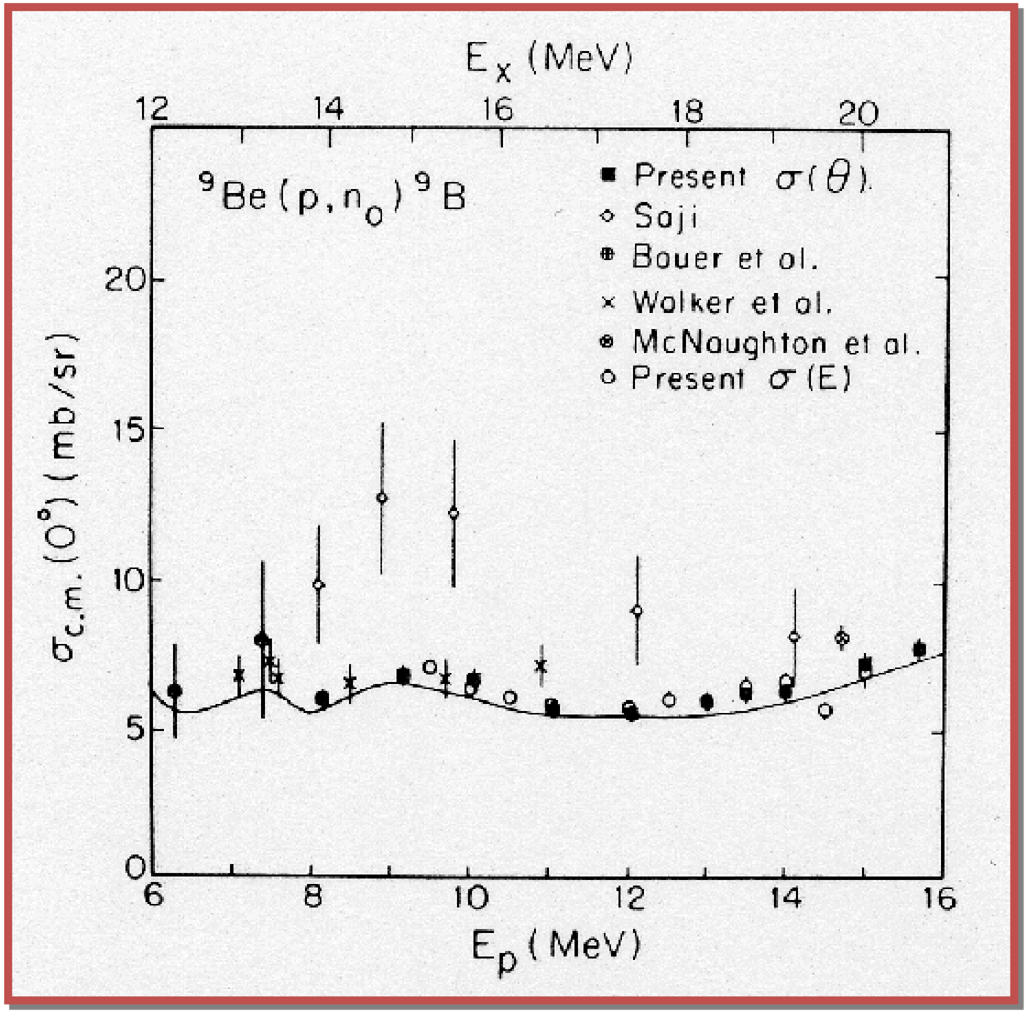
Cross Section as Function of Proton Beam Energy and Measurement Angles



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

- E_p increase → neutron yields rise at 0^O

Zero-degree Excitation Fucntion



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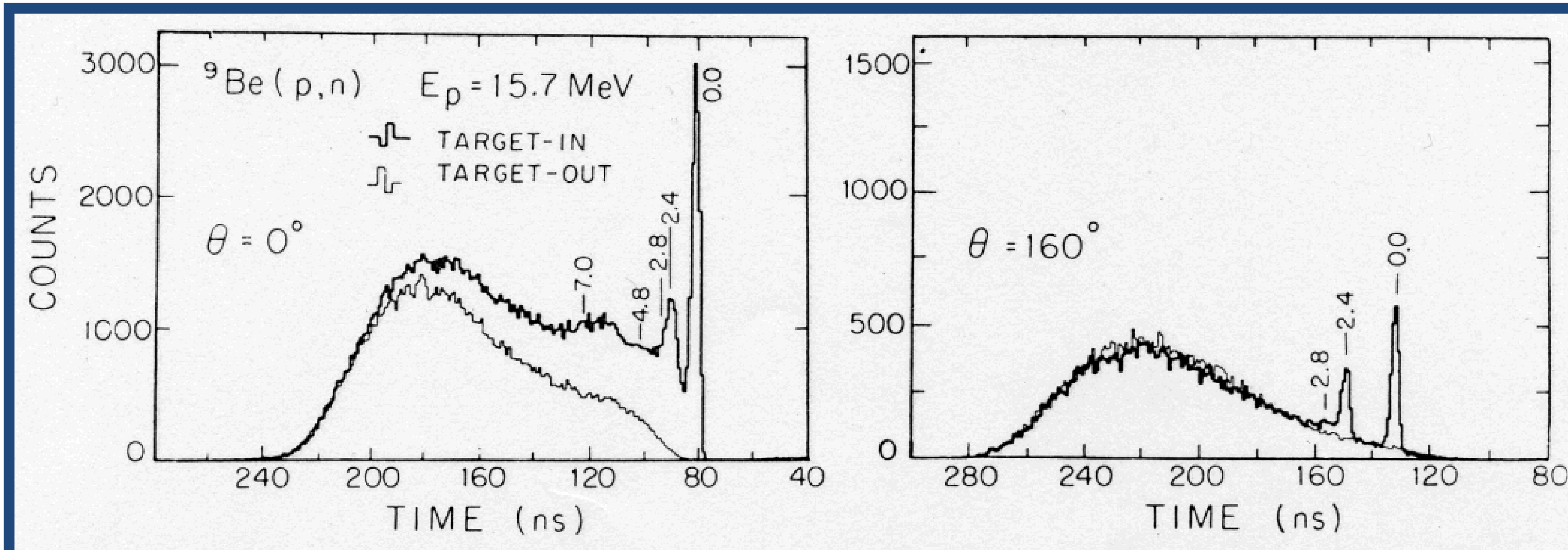
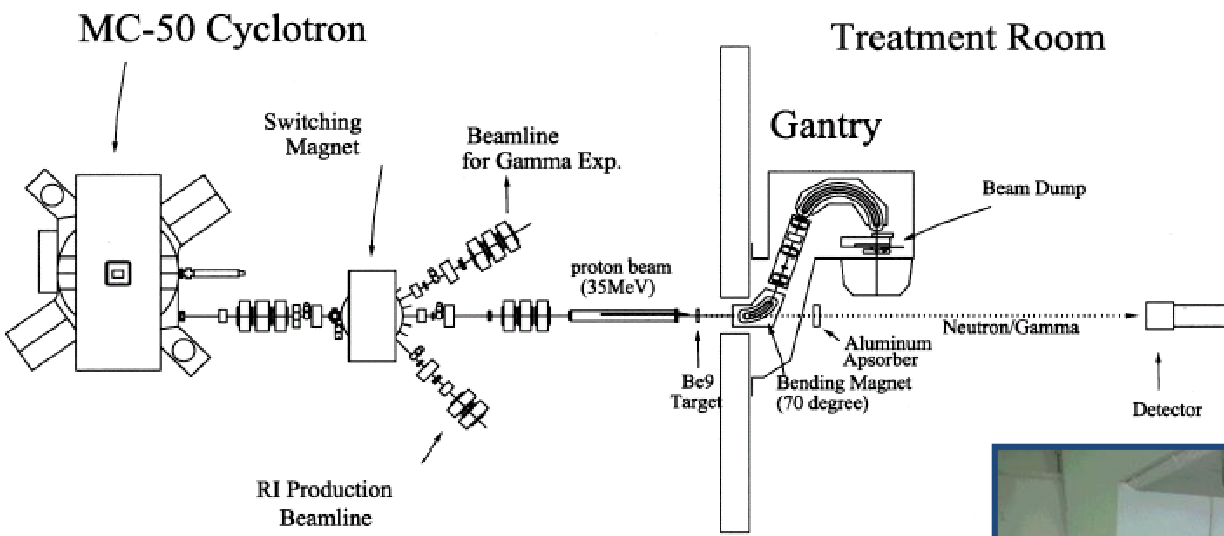
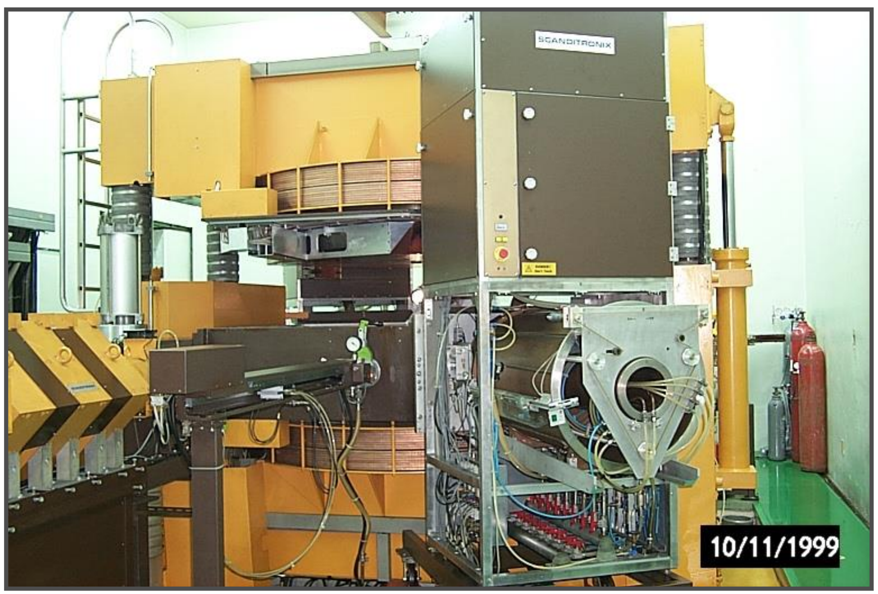
TOF Spectrum of n at $^{9}Be(p,n)^{9}B$ Reaction



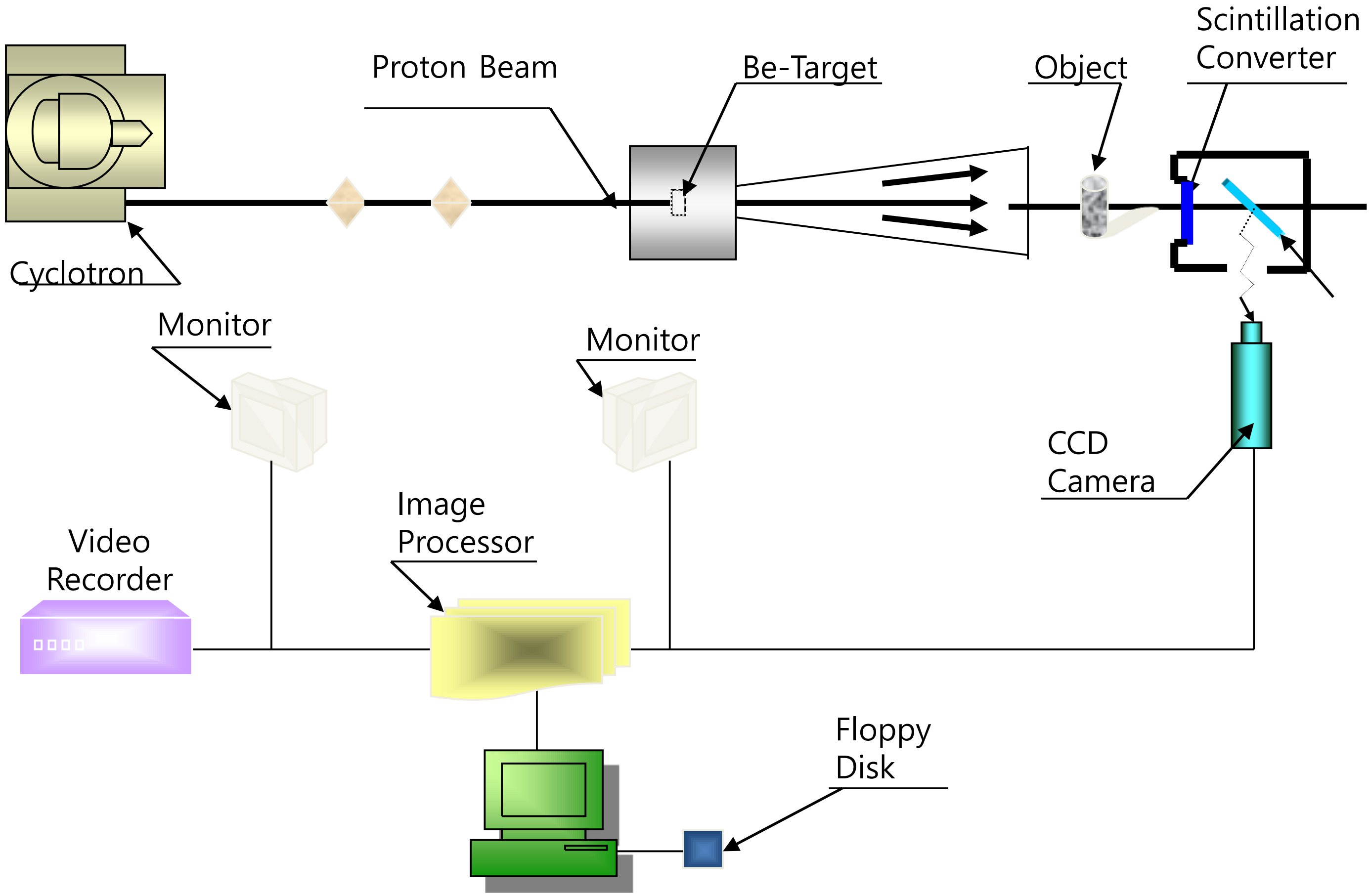
- Identification of the excite state structure of the residual nucleus by TOF spectrum

Cyclotron used for NR

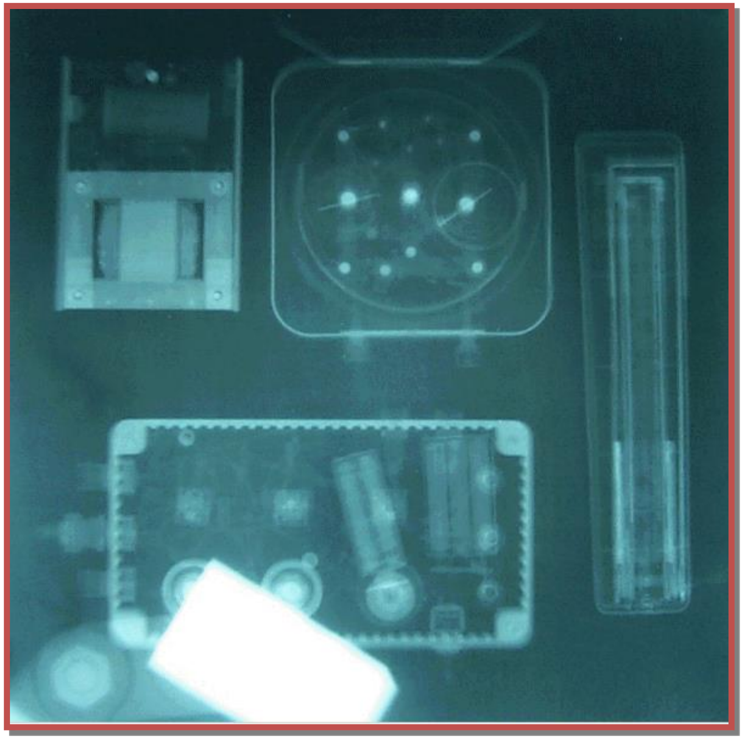




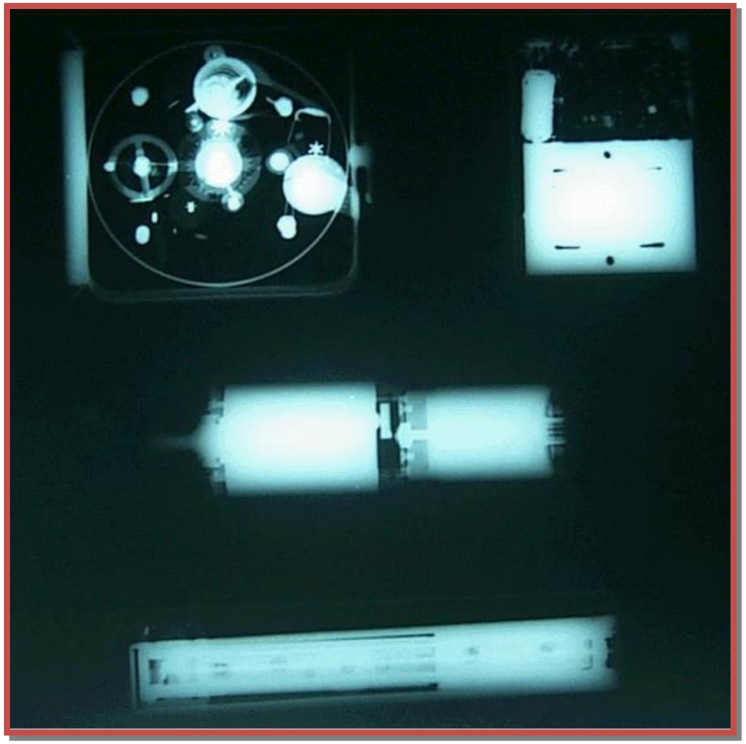
Schematic Diagram of Neutron Radiography System



Comparison of X-Radiography and Neutron Radiography



Neutron



X-ray(120keV)

Li-ion Battery Imaging by Neutron Radiography

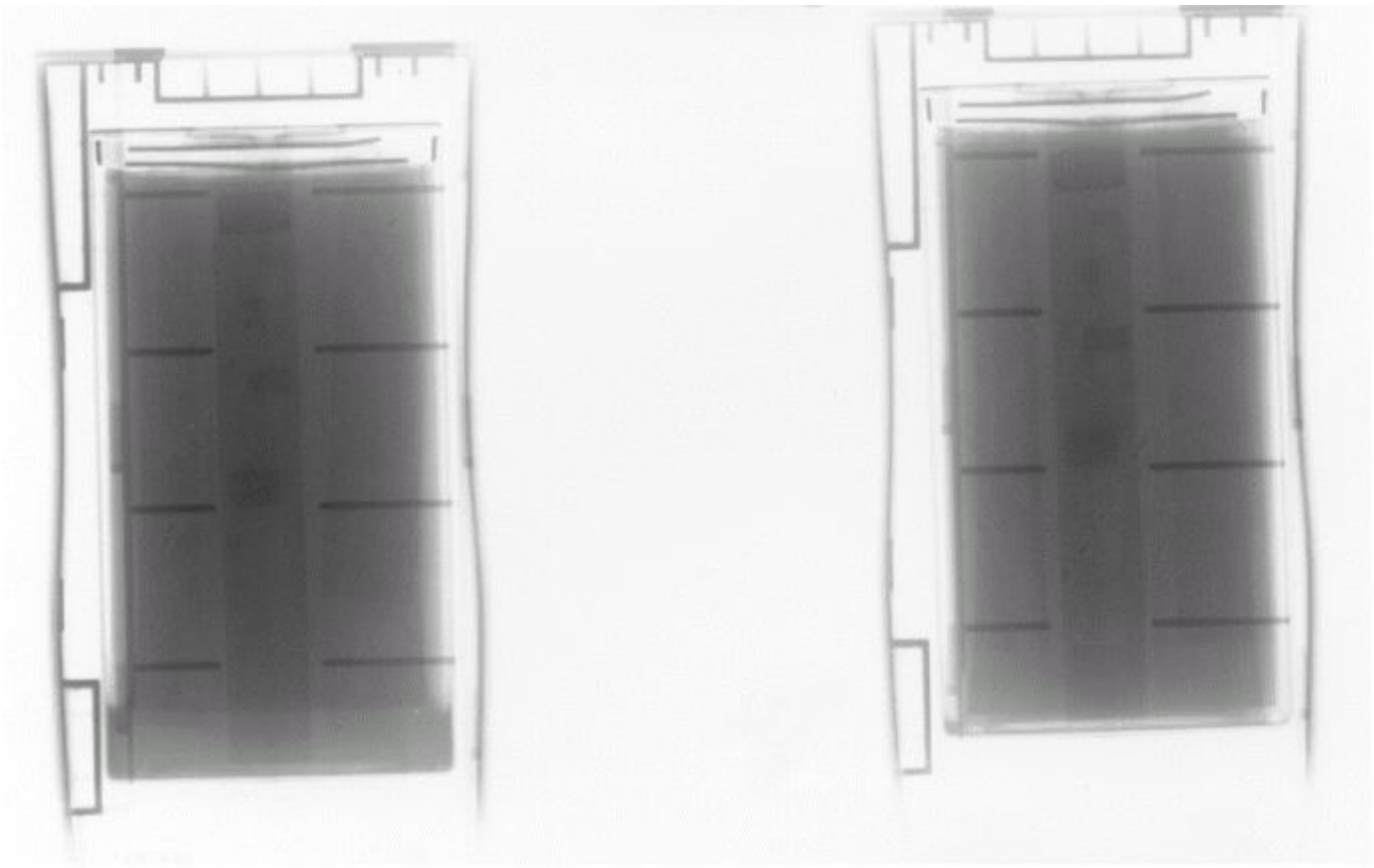
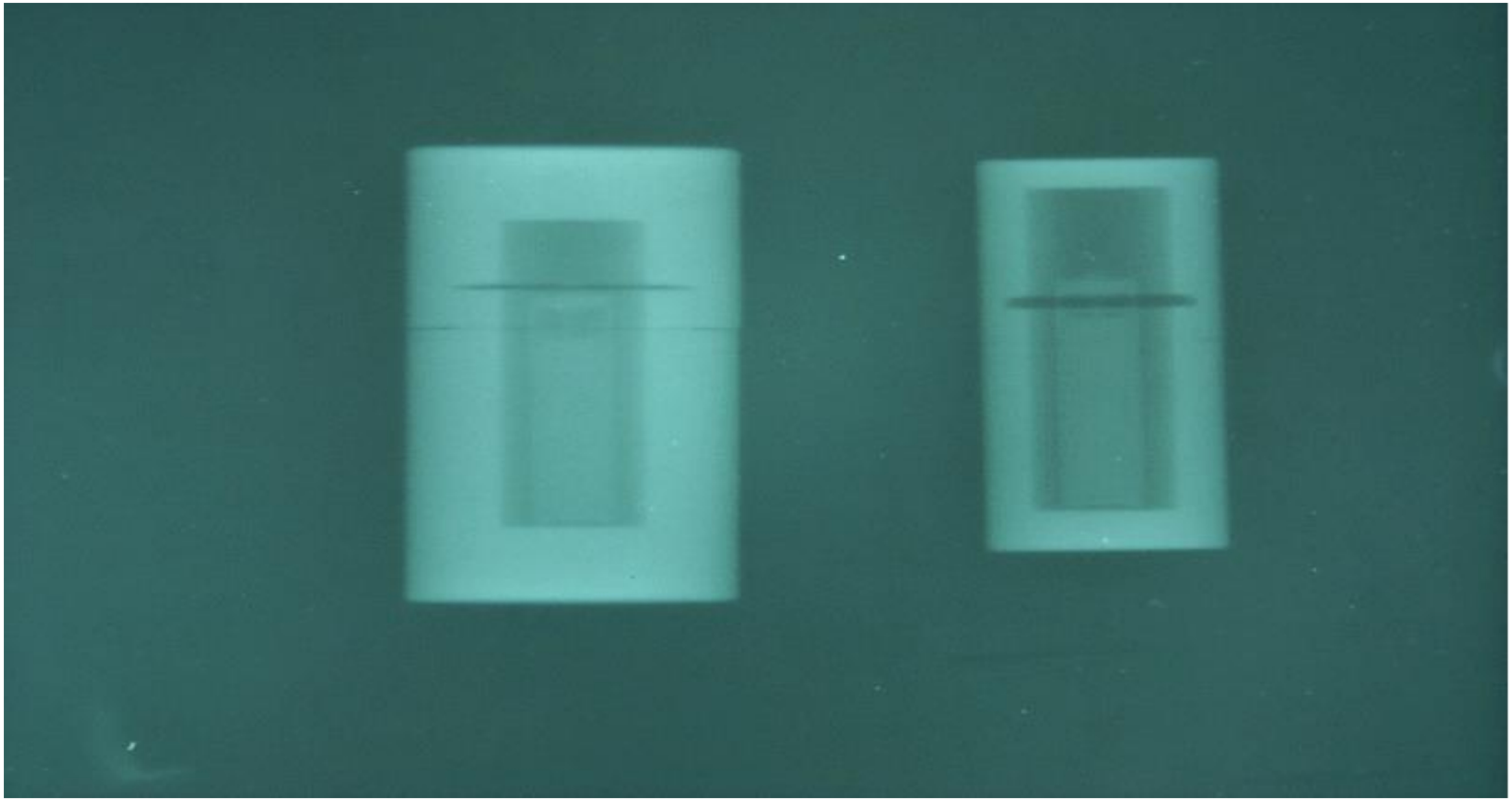
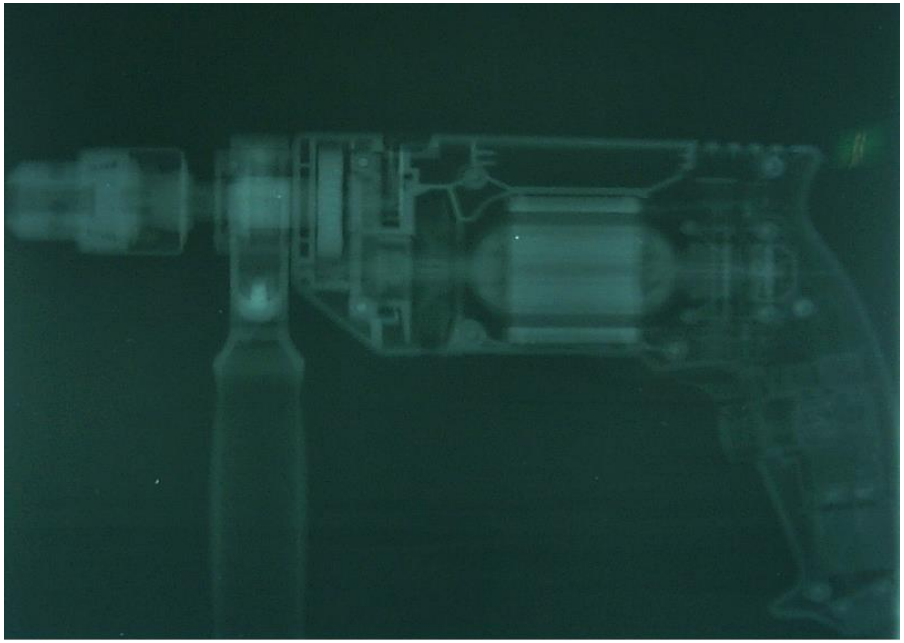


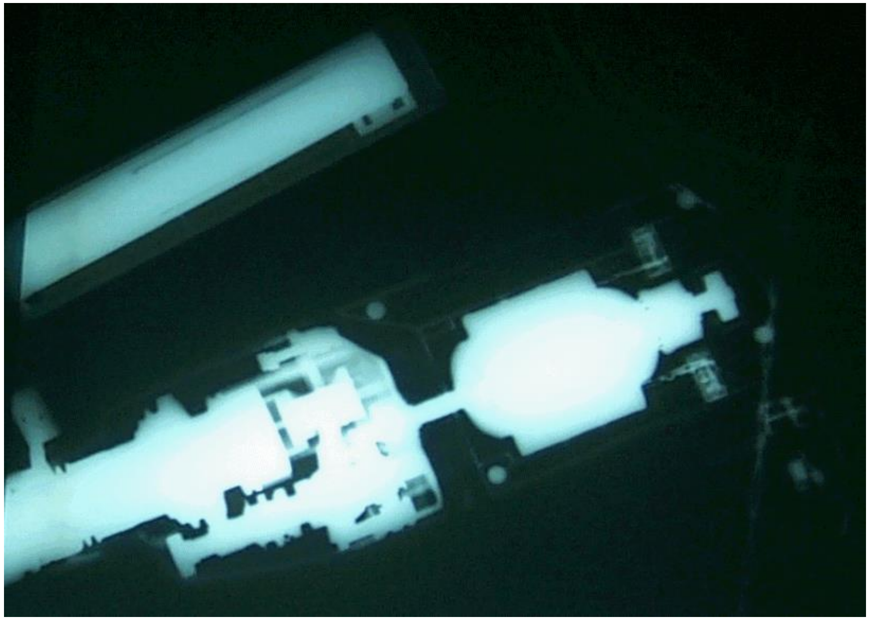
Image of Lead-Shielded Battery by Neutron Radiography



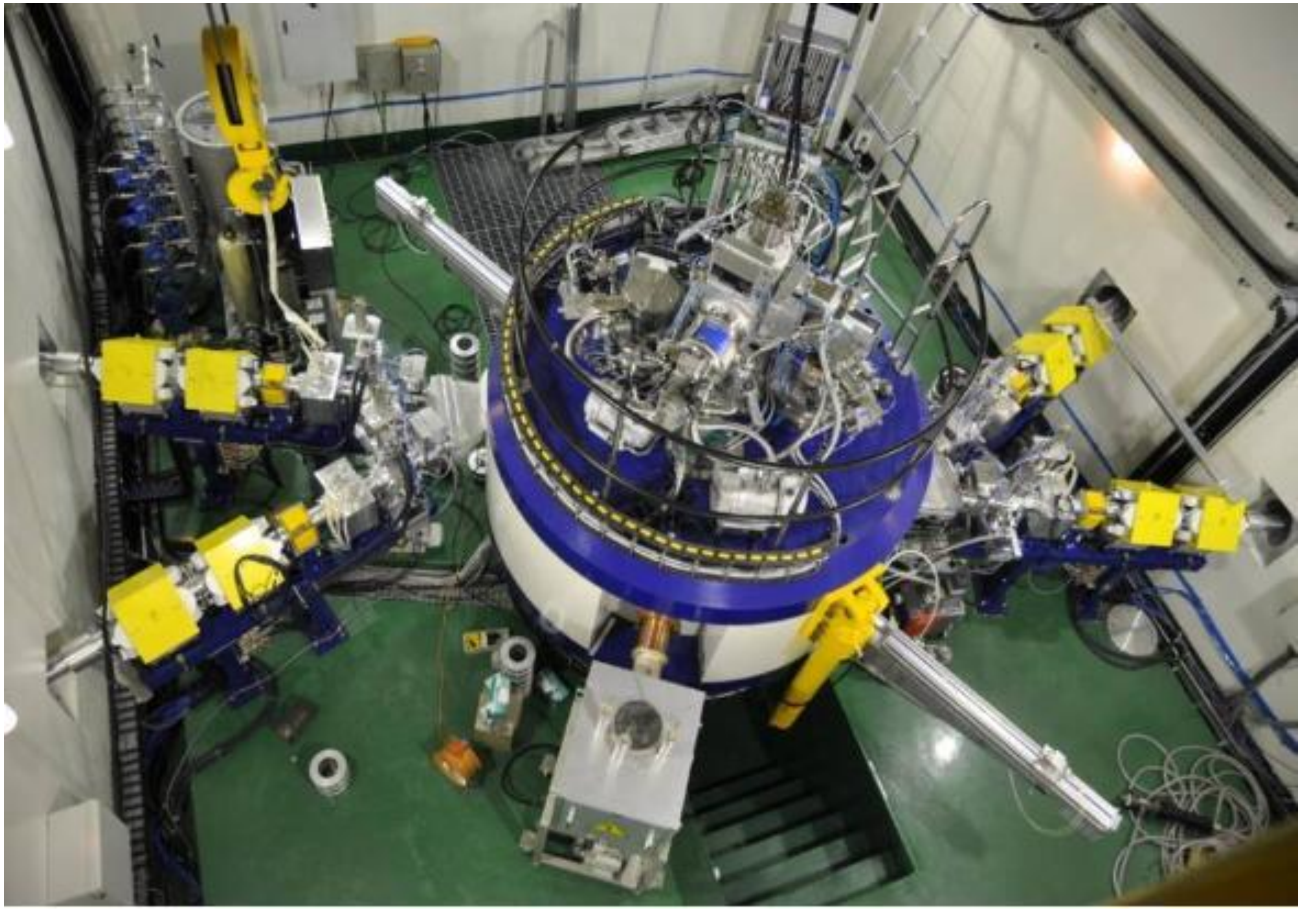
Comparison of X-ray and Neutron Radiography for Electrical Drill


neutron

X-ray

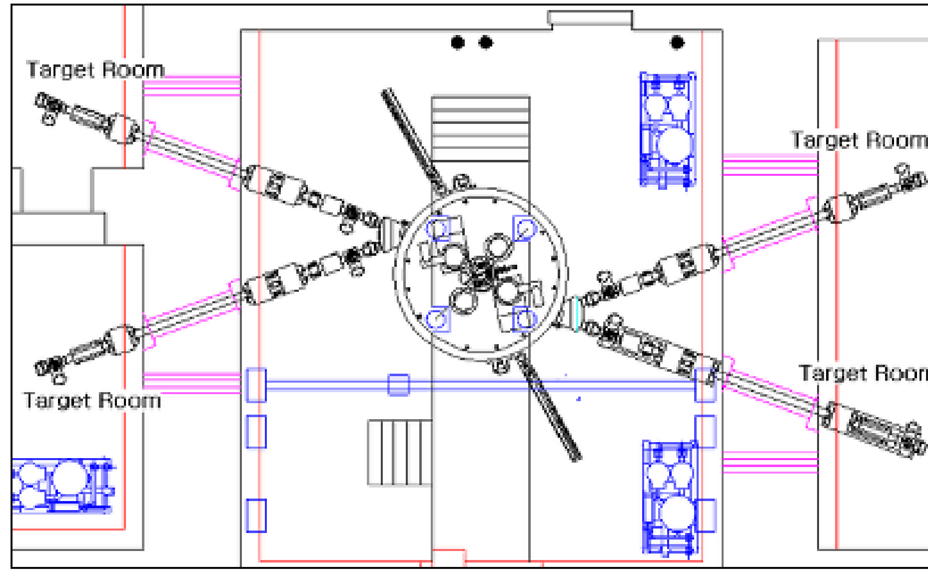


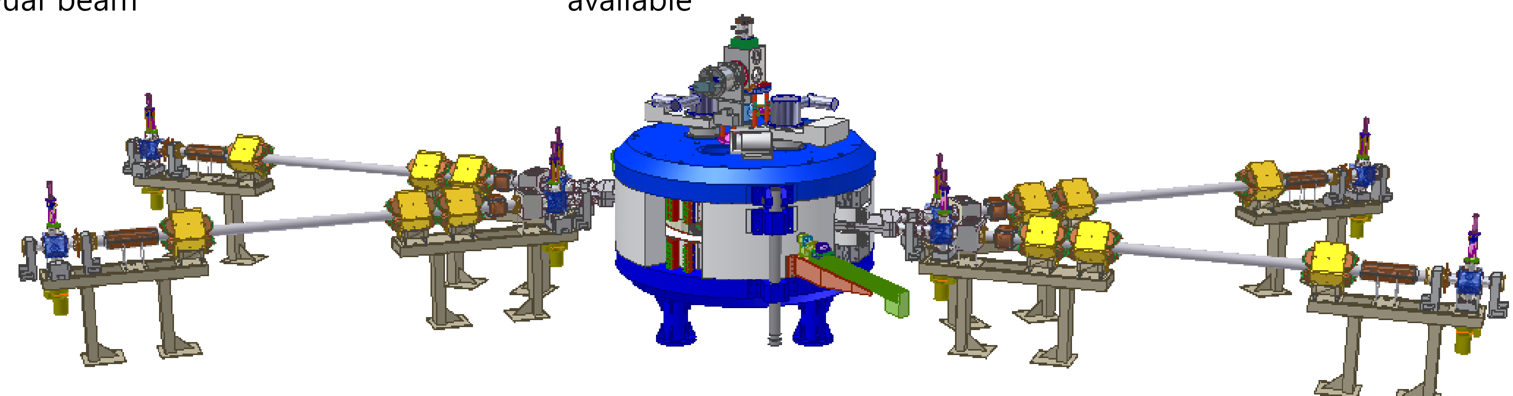
NR experimental facility at KAERI



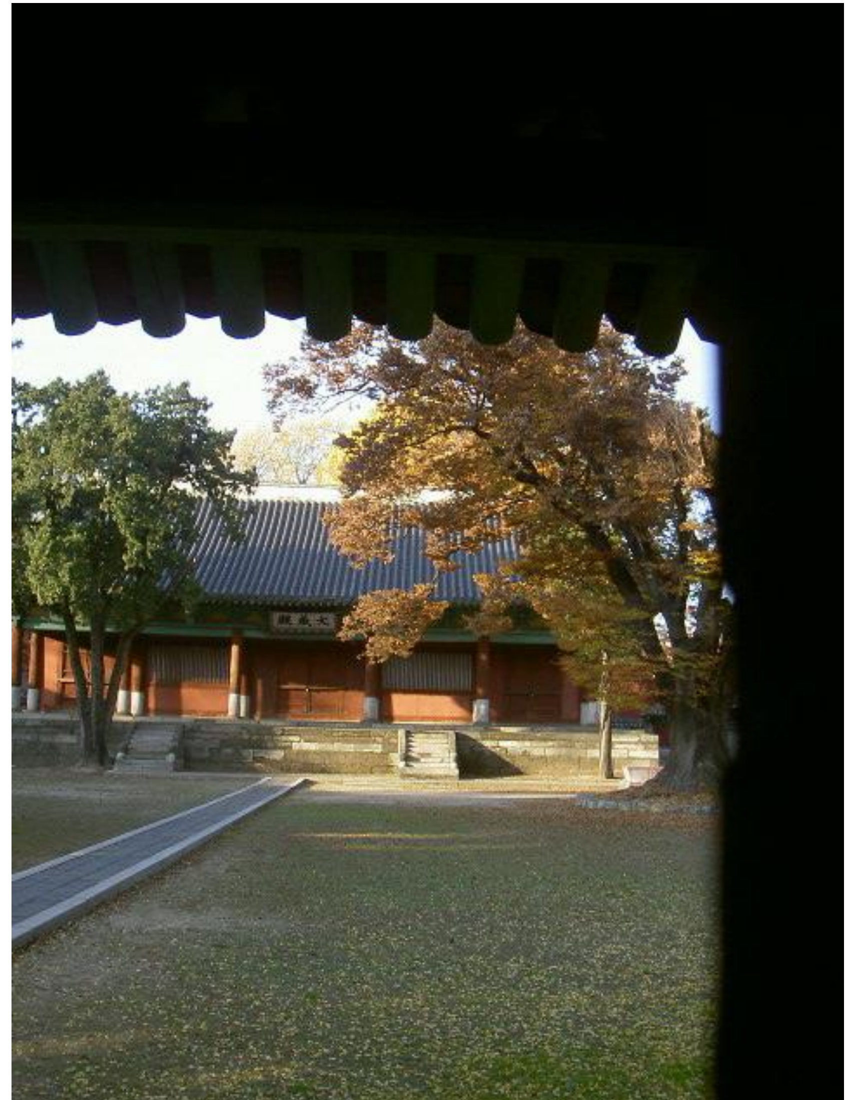
KIRAMS 30 – General Specifications

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

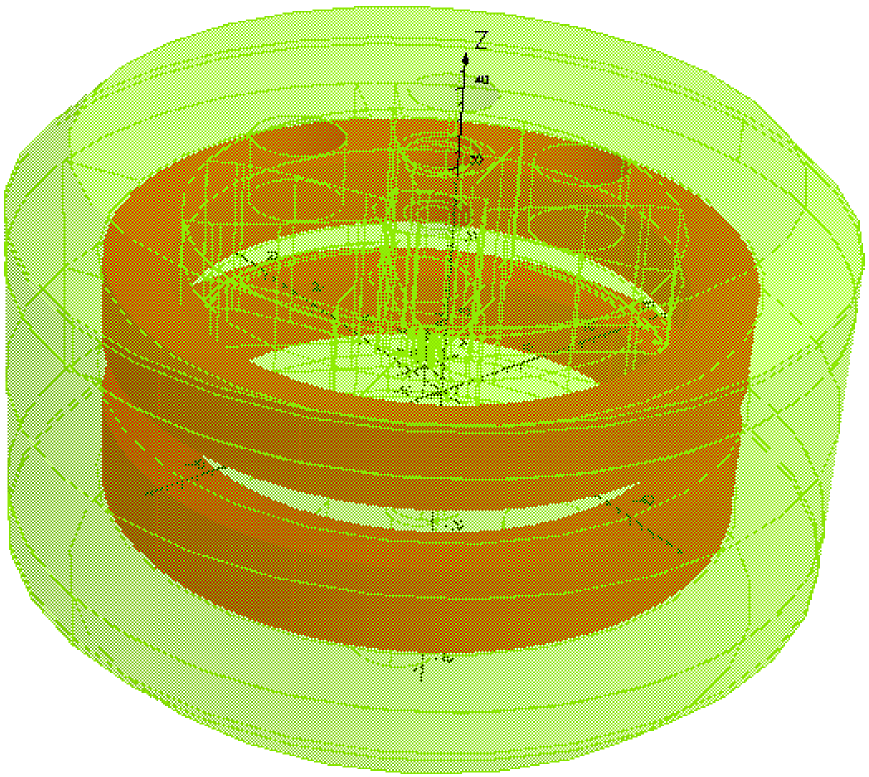
General Specification

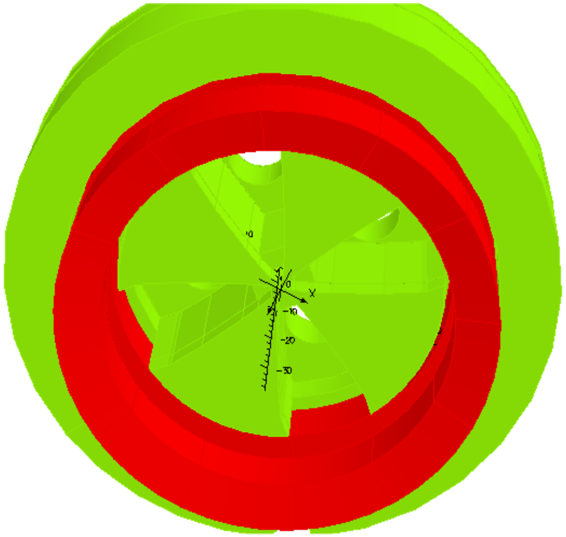
Parameters	Values
Particle	H^-
Extraction energy	4 MeV
Ion source	20 mA H^- multicusp
Injection energy	40 keV
Beam intensity	2 mA
Target	Be-Li hybrid

RF	
Harmonic number	4
RF frequency	48.83 MHz
Number of dees	2
Dee angle	43°
Dee voltage	50 kV
Coupling	Capacitive
Power	<50 kW

Magnet	
Number of sectors	4
B_0	0.8 T
Extraction radius	39.7 cm
Pole radius	45 cm
Hill/Valley gap	4 / 52 cm
Hill angle	> 40°
Coil dimension	7_{dpc} x 10 turns
NI / coil	28000 A-turns
Magnet dimension	Φ150, H82 cm
Power	~ 8 kW

Magnet System

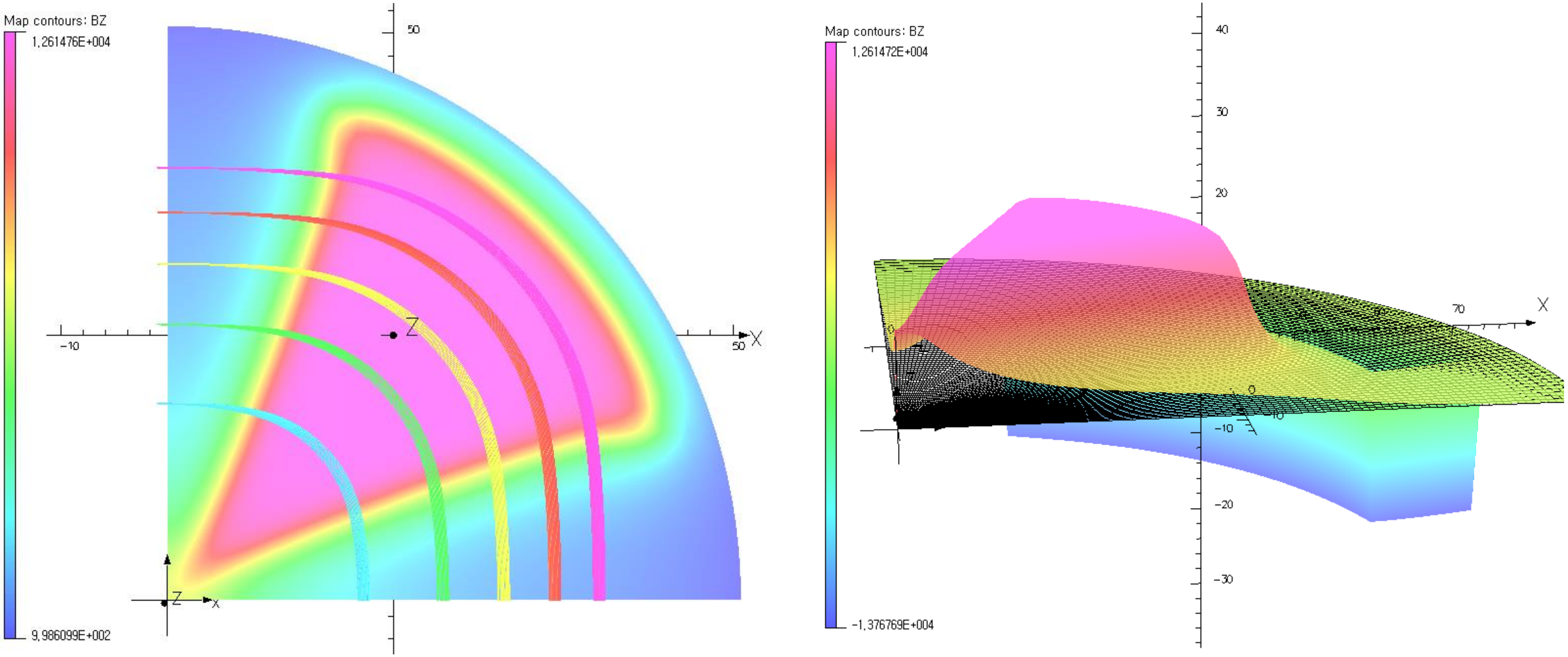




Prototypes of Magnet and Coils

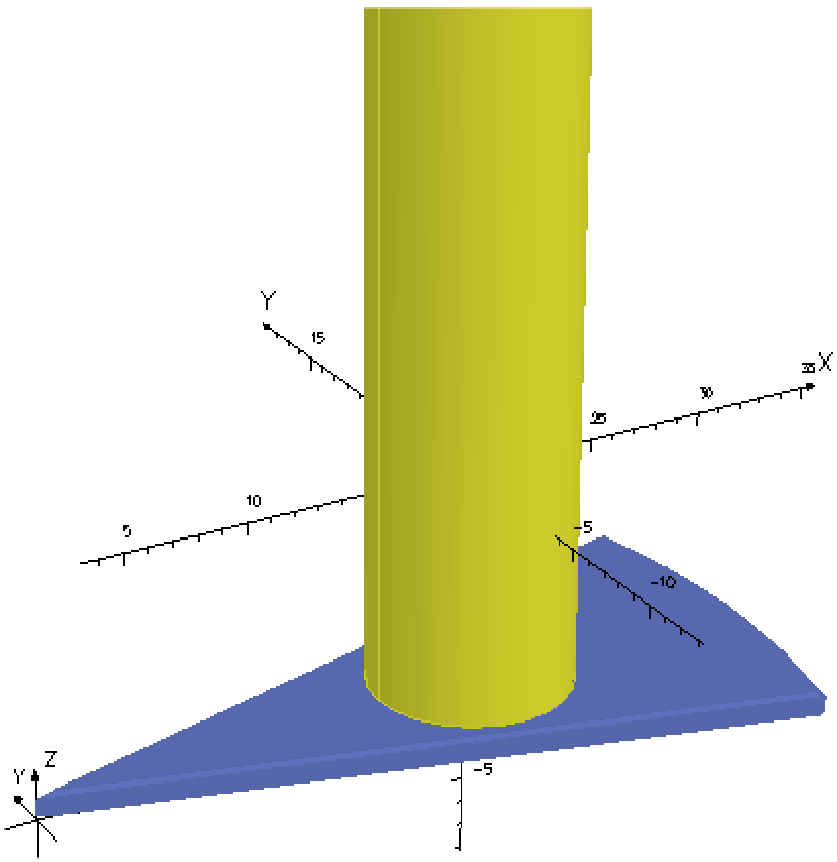
- Pancake type
- 4 Sector-magnet with deep valleys
- 4 holes for vacuum pump & RF cavity
- 1 central hole for axial injection

Magnet



Calculated magnetic field distribution and the equilibrium orbits (EO) when the energies are 1, 2, 3, and 4MeV.

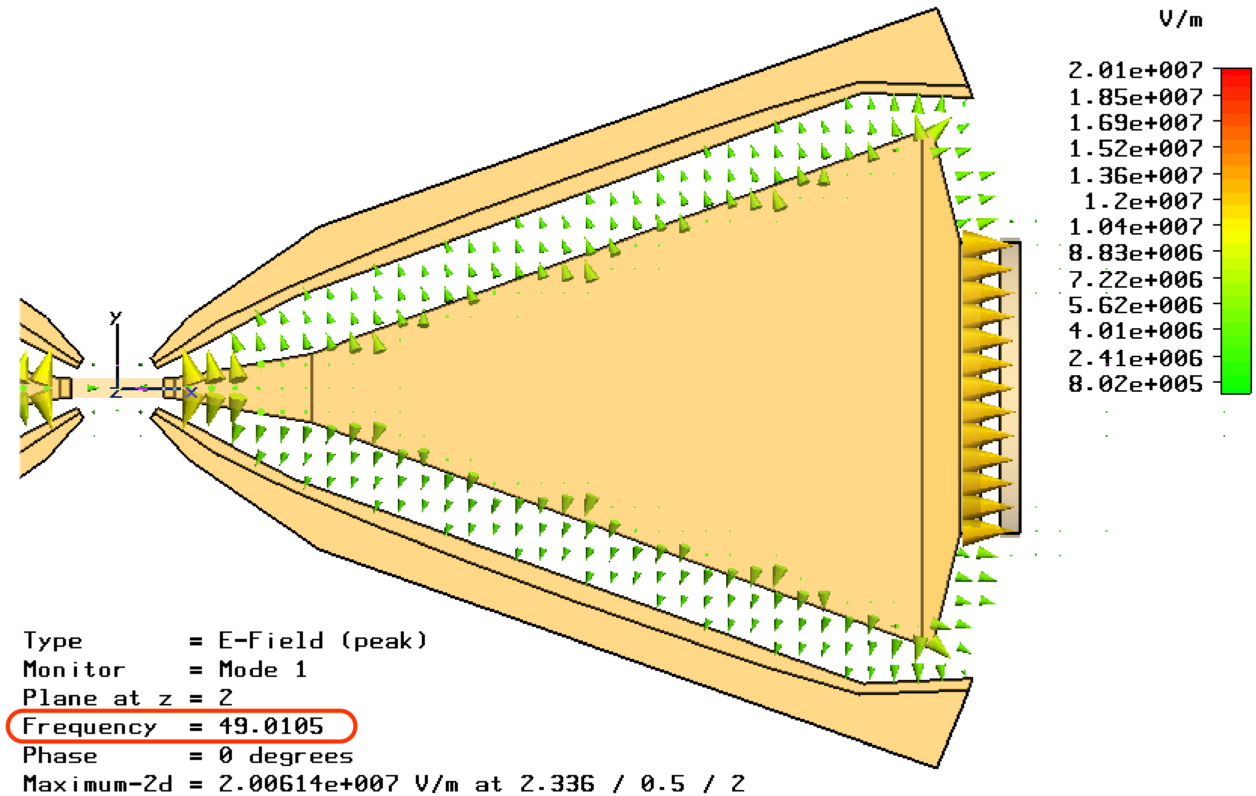
RF System



RF dee and cavity

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

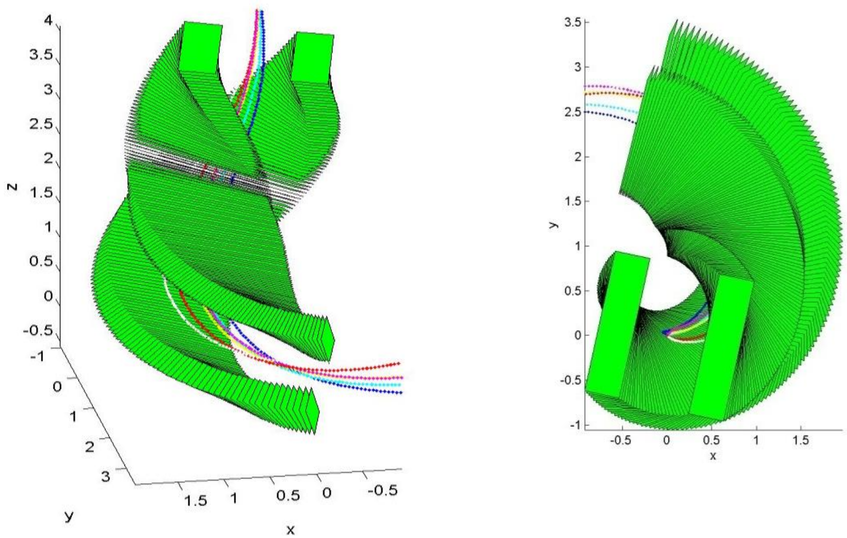
RF System



Required resonance frequency = 48.83 MHz

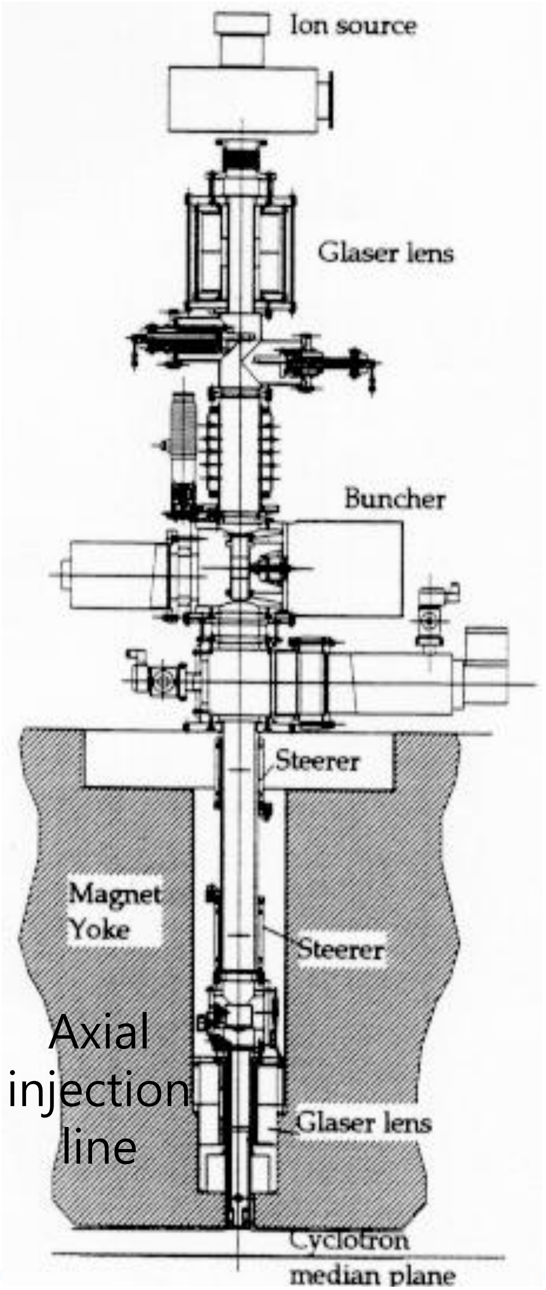
The electric field distribution between electrodes (dee and liner). The arrows represent the strength and the direction of the electric field. Q value is about 8600.

Injection System

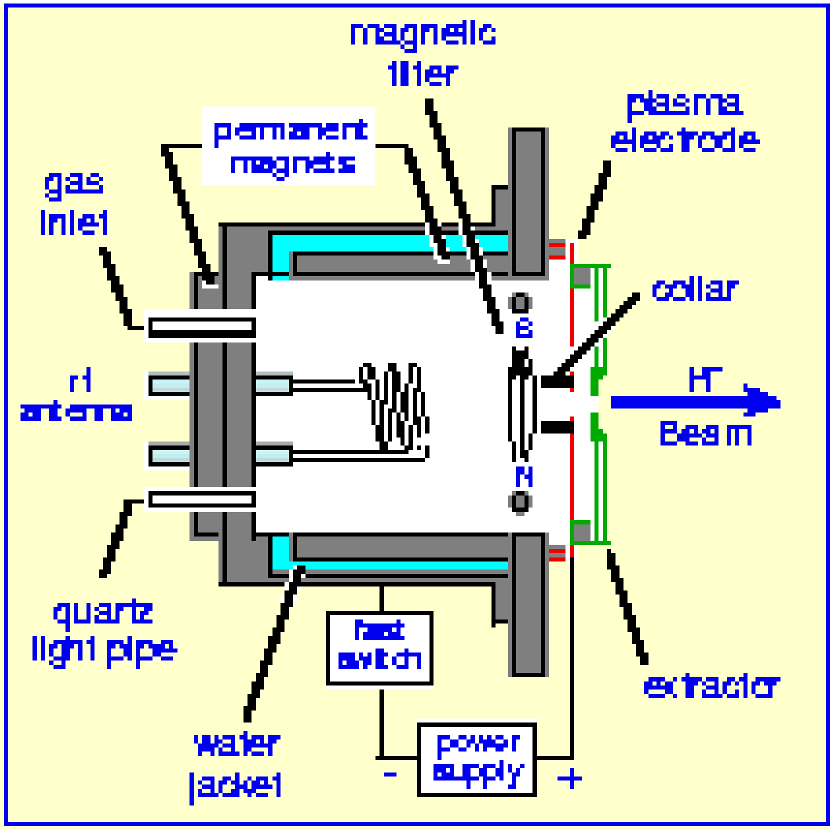


Spiral Inflector simulation results

- 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



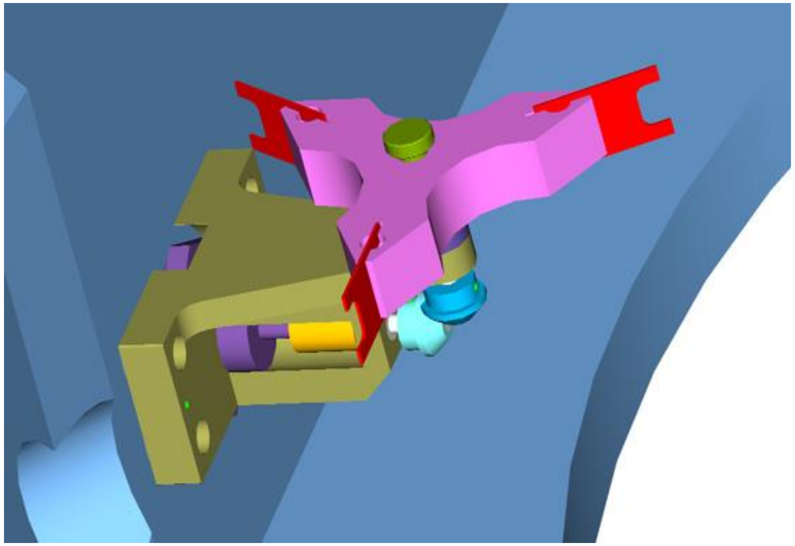
External Ion Source



Schematic of RF ion source

- Intensities of proton beam are limited in extraction
- The negative hydrogen ion is chosen as a 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

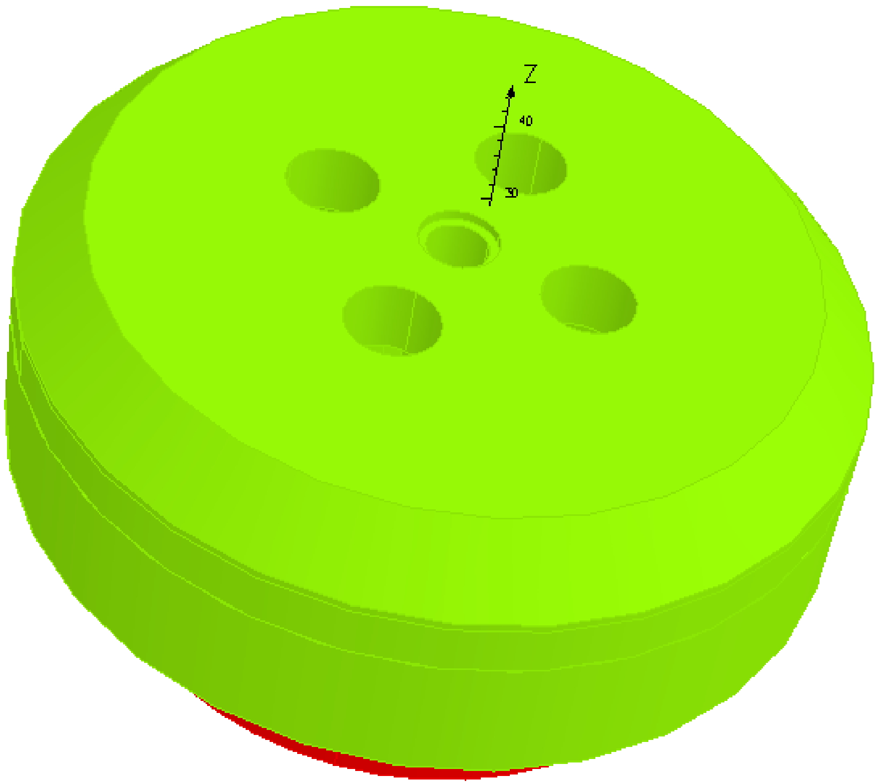
Extraction System



Extraction System of
SKKUCY-4

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

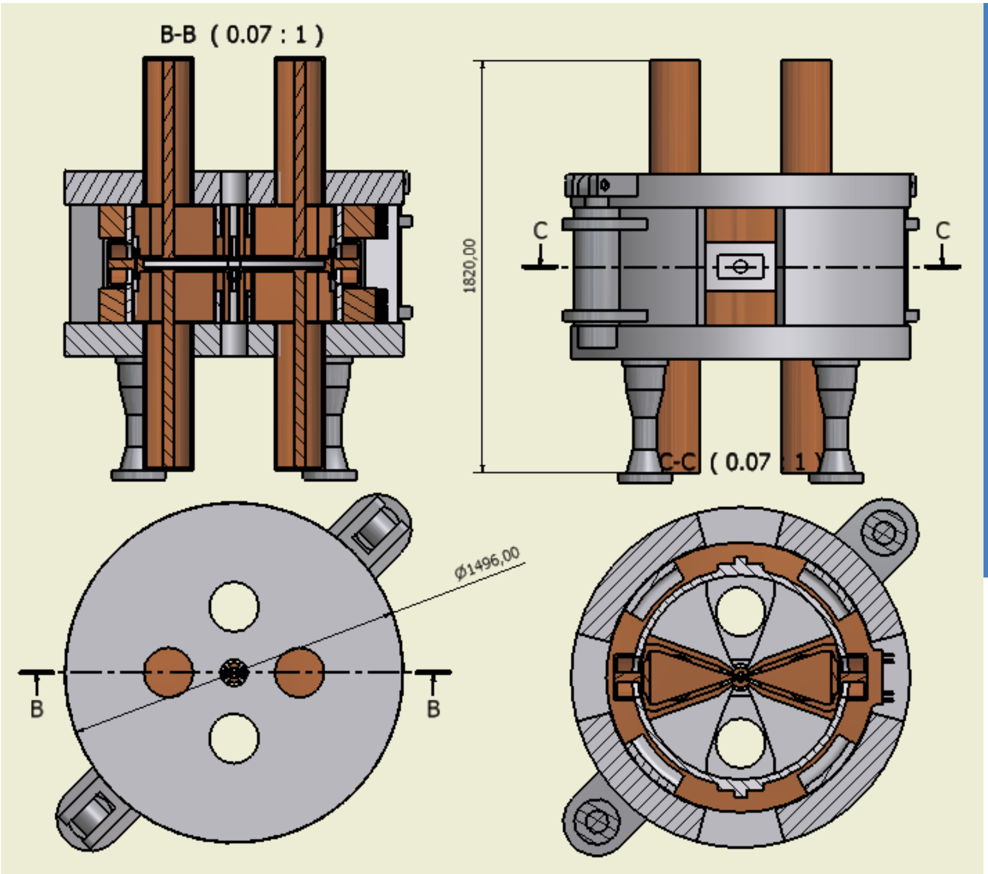
Vacuum System

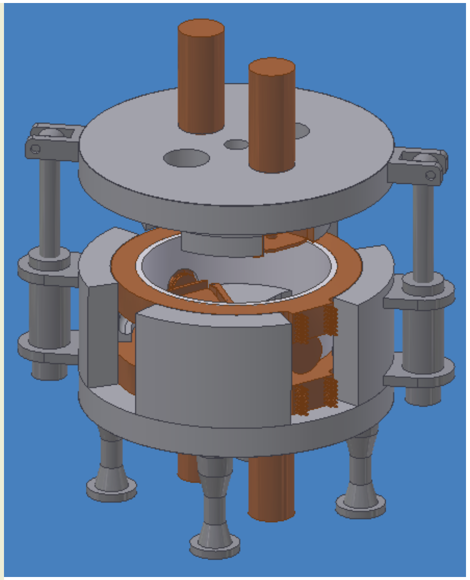


Bottom view of the magnet

- 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

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 ℃ (=453.54 K)**
- **Boiling point : 1350 ℃ (=1623 K)**
- **Chemical reaction**

i) $4Li+O_2 \longrightarrow 2Li_2O$

ii) $6Li+N_2 \longrightarrow 2Li_3N$

iii) $2Li+2H_2O \longrightarrow 2LiOH+H_2$

iv) $Li+4Cu \longrightarrow Cu_4Li$

- **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

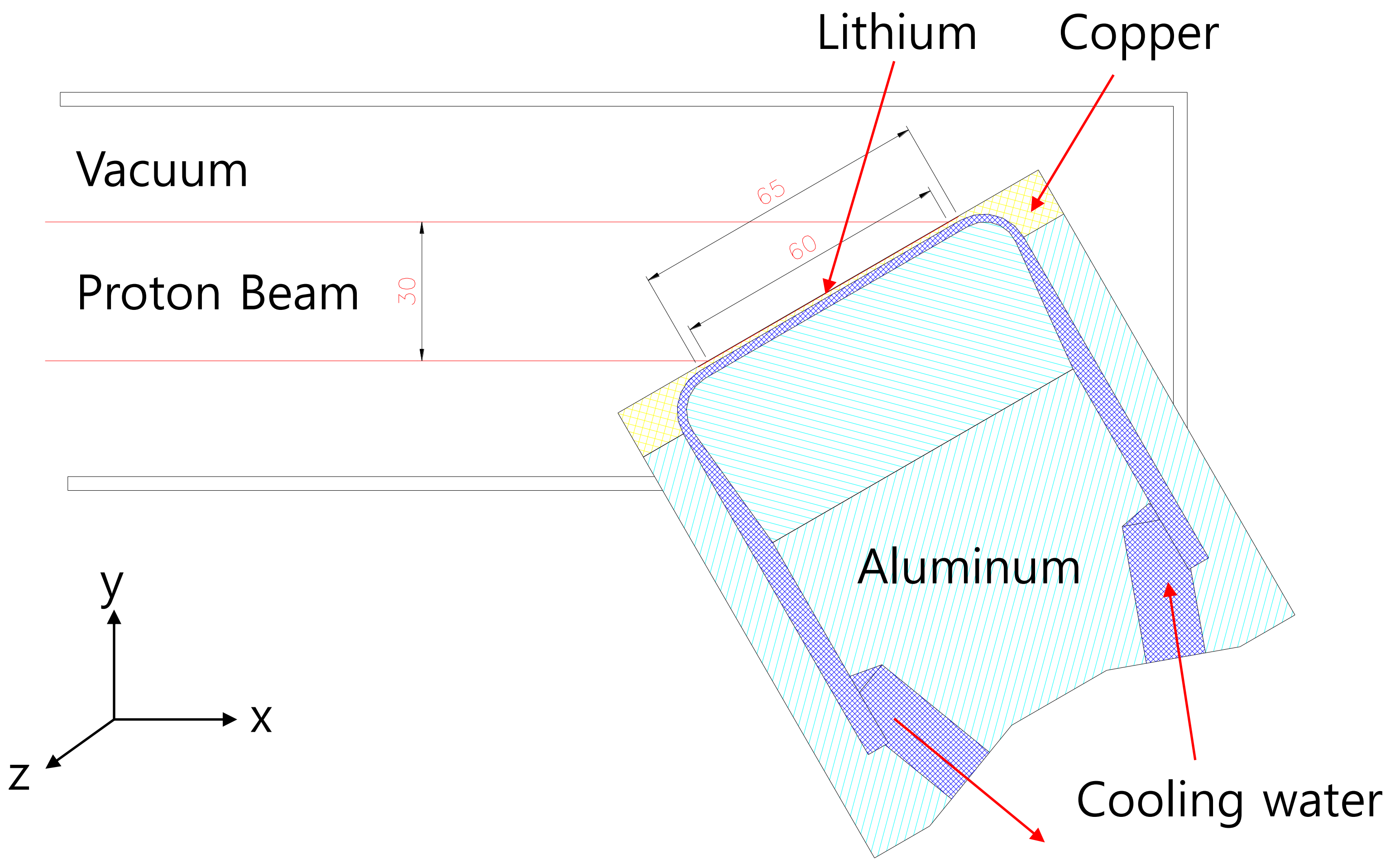
- Target material : Li
- Target thickness : 100 μm
- Target base : Cu
- Angle of inclination : 30 degree
- Energy absorption length : 200 μm
- Energy to Target : 1.7986 MeV

  Incident energy : 2.5 MeV

  Final energy : 0.7014 MeV

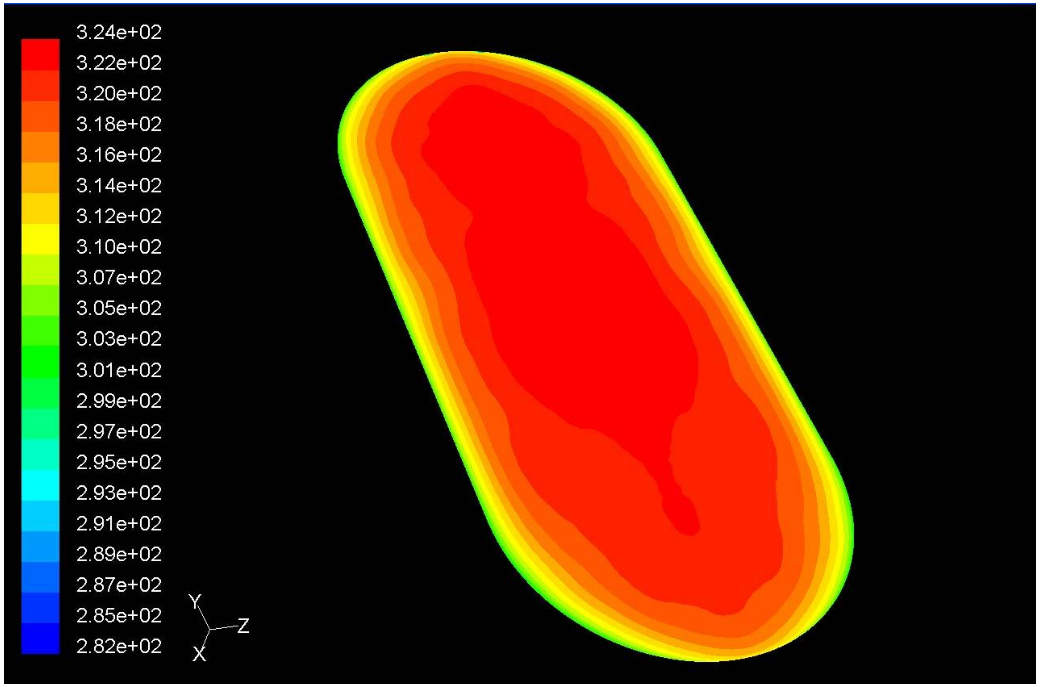
- Beam type : Proton
- Target size : 30 x 64 mm (ellipse)
- Irradiation area : 14.13 cm^2
- Cooling flow : 40 L/min (water)

Incident Energy / Absorption length	2.8MeV	2.5MeV
200 μm	1.4734	1.7986
300 μm	stopped	stopped


Lithium
Copper
Vacuum
Proton Beam
30
65
60
Aluminum
Cooling water
y
x
z

➢Analysis

- **Software : FLUENT**
- **Condition**
  - **1.7 MeV, 1 mA on Li**
  - **Angle : 30º**
  - **Thickness : 100μm**
  - **Flow rate : 40 L/min, 15 ℃**
- **Result**
  - **Maximum Temperature : 325 K (= 52 ℃)**



- **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

Parameters	Values
Beam	~ 2 mA of 4 MeV proton
Ion Source	External multi-cusp H^- ion source
Injection	Axial Injection using inflector
Magnet Sectors	4
Magnet Pole Diameter	~ 60 cm
Number of Dees	2
Harmonic Number	4
RF Frequency	~ 48.83 MHz
Extraction Method	Charge Exchange Carbon Stripper Foil

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