The current status of KBSI heavy ion accelerator project
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2. 28GHz SC ECR ion source
3. KBSI accelerator system
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Overview of KBSI Accelerator Project

**Motivation**
- Fast neutron radiography facility
- Achievement: High-yield neutron flux
- Implementation: Inverse kinematics
- Requirements: high beam current + windowless hydrogen target
- Pros.: compact size

**28 GHz ECR IS**
- 3 solenoids + 1 Hexapole SC magnet
- LHe re-condensing cryostat
- 28 GHz-10 kW gyrotron
- Large bore plasma chamber
- Output beam: 84 keV

**BEAM INTENSITY**
- Li$^3+$ higher than 1 mA

**LEBT System**
- enable to separate the ions from IS
- satisfy the RFQ input condition: beam acceptance, current, size and etc.
- 1 dipole + 3 solenoids + 2 quadrupoles
- 2 diagnostic chambers

**Linear Accelerator**
- Reference particle: Li$^3+$
- Freq.=165 MHz
- Output beam:
  - ~ 3.5 MeV@RFQ
  - ~ 18 MeV@DTL
(Li$^{2-3+}$ production $>1mA$)

KBSI Accelerator System Layout

$\text{p}(^7\text{Li}, \text{n})^7\text{Be}$ Inverse kinematics $\rightarrow$ Neutron production

$\sim 3.5\text{MeV}$

$\sim 18\text{MeV}$
Concept of neutron production

Normal kinematics

\[ ^3H(d,n)^4He \]
\[ ^2H(d,n)^3He \]
\[ ^7Li(p,n)^7Be \]

Normal kinematics: light particle interact with heavy element target. the produced neutron will be go to all direction.

Inverse kinematics: the produced neutron will be go forward. Production angle is limited about 30 degree. High intensity neutron beam.

Inverse kinematics

\[ p(^7Li,n)^7Be \]

Concept of the heavy ion linear accelerator based on compact sized neutron production.
Neutron yield

Requirement of KBSI Neutron Facility

→ Higher than 1pmA of Li^{2-3+} beam intensity
→ \sim 2.5\text{ MeV/u} (17.5\text{ MeV}) of beam energy
→ Gas target: >350\text{ Torr}
→ High efficiency detector for fast neutron detection

Fast Neutron Yield

\[ Y_n = F_{\text{Li}} \times \rho \frac{N_A}{A} \times L \times \sigma \]

\( Y \): Neutron yield
\( F_{\text{Li}} \): Beam flux
\( \rho \): Density
\( N_A \): Avogadro constant
\( A \): Atomic number
\( L \): Target length
\( \sigma \): Cross section

<table>
<thead>
<tr>
<th>Li energy (MeV/u)</th>
<th>Neutron yield (n/cm(^2)·s)</th>
<th>Limit angle (deg)</th>
<th>Maximum neutron energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.88</td>
<td>(8.5 \times 10^8)</td>
<td>\sim\text{few deg.}</td>
<td>1.88</td>
</tr>
<tr>
<td>1.9</td>
<td>(1.7 \times 10^{10})</td>
<td>4</td>
<td>2.1</td>
</tr>
<tr>
<td>1.92</td>
<td>(3.6 \times 10^{10})</td>
<td>7</td>
<td>2.3</td>
</tr>
<tr>
<td>2.5</td>
<td>(1.0 \times 10^{12})</td>
<td>28</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Application of neutron

Neutron Radiography

Scan image using gamma ray

Scan image using neutron

J.E. Eberhardt et al. / Applied Radiation and Isotopes 63 (2005)
28GHz SC ECR ion source
28GHz SC ECR ion source

Layout of KBSI ECR ion source

- 28GHz-10kW gyrotron
- SC magnet power source
- Plasma chamber
- Superconducting magnet system
- HV extraction
- Liq-He Recondensing cryostat
- Recondensor
- Waveguide
28 GHz Microwave Power Source

Output: 2kW

<table>
<thead>
<tr>
<th>Location</th>
<th>Components</th>
<th>MW Transmitted power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>Directional coupler</td>
<td>1.9</td>
</tr>
<tr>
<td>1</td>
<td>Default+mode converter</td>
<td>1.891</td>
</tr>
<tr>
<td>2</td>
<td>1+mode filter</td>
<td>1.886</td>
</tr>
<tr>
<td>3</td>
<td>2+ 90° bend</td>
<td>1.886</td>
</tr>
<tr>
<td>4</td>
<td>3+dc break</td>
<td>1.877</td>
</tr>
</tbody>
</table>

Test condition: Gyrotron output = 28 GHz, 2 kW
Plasma Chamber & Extraction System

Plasma Chamber
- Assembly
  - Moving System for bias disk and oven
  - Vacuum Spec.
    - Operating: 10^{-5} Torr
    - Initial and waiting: 10^{-8}~10^{-9} Torr

Electrode System
- Isolated water cooling system (Q>15L/min)

Connected high voltage power (max. 30kV)
- Extraction Chamber (Grounded)
- Moving System for Electrode
- Gas Supply System
- TMP 1100 L/sec
- Isolation (Ta 2mm, Kapton 1mm)
Superconducting magnet system

3 Solenoid + 1 hexapole magnet (6 step-type coils)

The magnetic field distributions in the plasma chamber were obtained from Opera.

- The axial field: 3.5 T at injection, 2.2 T at extraction.
- The minimum axial field (modifiable): 0.4 ~ 0.8 T.
- The radial design field on the plasma chamber wall: 2.1 T
Superconducting magnet system

Two candidates considering domestic vendor technology

- Saddle type is the best but it difficult to wind by domestic supplier
- By adopting, the **step-type hexapole** modified from racetrack and saddle coils, we could increase the magnetic field of radial field.

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**Racetrack type**

**Step type**
Superconducting magnet system

Magnet test at open-type cryostat

- Before final assembly, separate coil performance was checked
- Vertical cryostat (open type) was prepared for convenient test
- Magnet status, temperature, magnetic field were observed

13th International Conference on Heavy Ion Accelerator Technology
Superconducting magnet system

The separate coil performance

- Solenoid coils satisfied the requirements of operating current.
- Hexapole have not reached the final values yet (83% of $I_{op}$).
- Needs reinforcement of hexapole magnets
Superconducting magnet system

**Cryostat**

For the LHe recondensing on the cryostat
- 4 GM cryocoolers
- 4 LHe recondenser
- HTS current lead:
  - 300 A (6 ea), 500 A (2ea)
- temperature monitor: 7 cernox sensors
- level monitor: 2 LHe level sensors

A cryocooler works the two stages operating at 4.2 K on the second stage and 50 K on the first stage. Cooling capacity of each stage is 1.5 W and 50 W, respectively.
Superconducting magnet system

The comparison of magnet field between design and experimental values

<table>
<thead>
<tr>
<th>Magnet current</th>
<th>HP</th>
<th>Sol</th>
</tr>
</thead>
<tbody>
<tr>
<td>38A</td>
<td>20A</td>
<td></td>
</tr>
<tr>
<td>51A</td>
<td>40A</td>
<td></td>
</tr>
<tr>
<td>78A</td>
<td>60A</td>
<td></td>
</tr>
<tr>
<td>100A</td>
<td>80A</td>
<td></td>
</tr>
</tbody>
</table>

From bottom to Top

Blue: HP, Reds: Sol.
Solid lines: design, Symbols: experimental

Good agreement was observed
Operation of 28 GHz SC ECR ion source

- The ECR plasma was generated in last year
- The first beam was extracted from 28 GHz ECR ion source this year
- Optimization of ECR ion source with various conditions is under way
- Beam spectrum as well as x-ray from ion source
- Further study about ECR ion source will be conducted

X-ray measurement

Ar beam spectrum

O beam spectrum
Beam measurement system in LEBT

- Extracted beam spectrum was measured using dipole magnet.
- Also, x-ray from plasma chamber was measured with x-ray detection system.

28 GHz ECRIS

Bending Magnet

X-ray detection system

Collimator

CZT Detector

View Port

Beam diagnostic system

View screen

Slits

Faraday cup

Window for beam profile monitor

Wire scanner
KBSI Accelerator System
Progress of Accelerator Development

Radio-Frequency Quadrupole (RFQ)

- Design of RFQ is concluded (4-vane type)
- Total length of RFQ: < 2.4 m
- Particle transmission rate: > 98%
- Beam energy: 3.5 MeV
- The KBSI RFQ and 100 kW RF power source are scheduled to be completed in this year

Drift Tube Linac (DTL)

- By the conceptual design of DTL, we will adopt IH type DTL for the high electric power efficiency.
- Beam energy: ~ 18 MeV
Radio-Frequency Quadrupole (RFQ)
## Design specification of RFQ

### Beam dynamics

<table>
<thead>
<tr>
<th>Particle</th>
<th>( \text{Li}^3+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Energy</td>
<td>12 keV/u</td>
</tr>
<tr>
<td>Output Energy</td>
<td>500 keV/u</td>
</tr>
<tr>
<td>Max. Beam Current</td>
<td>1 pmA</td>
</tr>
<tr>
<td>Input Transverse Emittance</td>
<td>0.2 ( \text{pi.mm.mrad} )</td>
</tr>
<tr>
<td>Max. Emittance Increase</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>Min. Beam Transmission</td>
<td>&gt;95%</td>
</tr>
</tbody>
</table>

### RF structure

<table>
<thead>
<tr>
<th>Cavity Structure</th>
<th>4 vane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Design</td>
<td>Brazed structure with Octagonal shape</td>
</tr>
<tr>
<td>Frequency Quadrupole mode</td>
<td>165 MHz</td>
</tr>
<tr>
<td>Max. Duty Cycle</td>
<td>CW mode</td>
</tr>
<tr>
<td>Max. Surface Fields</td>
<td>&lt;1.7 Kilp.</td>
</tr>
</tbody>
</table>
## Design Parameters of the RFQ

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vane voltage</td>
<td>55</td>
<td>kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>1</td>
<td>pmA</td>
</tr>
<tr>
<td>Modulation parameter, m</td>
<td>1 ~ 2.08</td>
<td></td>
</tr>
<tr>
<td>Transverse focusing parameter, B</td>
<td>&lt;6</td>
<td></td>
</tr>
<tr>
<td>Synchronous phase, φ_s</td>
<td>-90→-30</td>
<td>Deg</td>
</tr>
<tr>
<td>Maximum surface electric field</td>
<td>&lt;20.2 (1.5kilp.)</td>
<td>MV/m</td>
</tr>
<tr>
<td>Transmission efficiency</td>
<td>&gt;97</td>
<td>%</td>
</tr>
<tr>
<td>Total length</td>
<td>2324.8</td>
<td>mm</td>
</tr>
<tr>
<td>Input emittance, ε_{x,y,rms,n}</td>
<td>0.187</td>
<td>mm.mrad</td>
</tr>
<tr>
<td>Output emittance, ε_{x,rms,n}</td>
<td>0.213</td>
<td>mm.mrad</td>
</tr>
<tr>
<td></td>
<td>0.211</td>
<td>mm.mrad</td>
</tr>
<tr>
<td></td>
<td>0.051</td>
<td>MeV.deg/u</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Beam dynamics simulation

Beam transmission

- Beam transmission rate: >98.9%
- Beam energy: >500 keV/u

Beam profile
RFQ vane design parameters
Design of RFQ cavity

- Resonance frequency: 165 MHz
- Field flatness: \(<\pm 2.5\%\)
- Tuner sensitivity: 0.117 MHz/mm
- span between two mode(dipole & quadrupole): >4 MHz
Design & fabrication of RFQ cavity

- Resonance frequency: 165 MHz
- Field flatness: <±2.5%
- Tuner sensitivity: 0.117 MHz/mm
- Span between two mode (dipole & quadrupole): >4 MHz
Interdigital-H (IH) type DTL

- High Shunt impedance of Interdigital H (IH) Structure
- IH structures have high electric power efficiency in low energy region
- Best choice for the accelerator with compactness and low electric power

Shunt impedances vs. Beam velocities for different structures

Courtesy of Prof. T. Hatori @ NIRS
Beam dynamics simulation - preliminary study

- Total length of DTL: < 2.3 m
- Particle transmission rate: > 92%
- Beam energy: 2.7 MeV/u
- More research for DTL is under way

Courtesy of Dr. S. Ogata @ Atelier Modeling
Future plan

- Optimization of ECR ion source operational condition
- Beam diagnosis under LEBT operation
- Beam acceleration using RFQ LINAC
- Engineering design of Drift Tube LINAC
- Design of neutron application
Thank You For Your Attention!