Review of Accelerator-based Boron Neutron Capture Therapy

IPAC16

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Okinawa Institute of Science and Technology (OIST)

May 12, 2016
Principle of BNCT

Beam collimator

Tumor area

Neutron source (reactor)

Normal cell

Tumor cell

Cell-level feature
Transfer Boron to tumor cell with selective drug-delivery.
Neutron reacts with boron and emits an a-particle.

Principle of BNCT

Neutron source (reactor)

Tumor area

a-particle

Normal cell

Tumor cell

a and Li-particle

Cell-level feature

Neutron reacts with boron and emits an a-particle.
Principle of BNCT

Neutron source (reactor)

Cell-level feature

a and Li-particle kills tumor cell selectively

Courtesy of H. Kumada
Only Slow neutron reacts with boron

Cross-section of nuclear reaction

- Boron
- Oxygen
- Carbon

Neutron energy (eV)

0.01 1 10 100 1000 10000 100000

0.000001 0.00001 0.0001 0.001 0.01 0.1 1 10 100 1000 10000

Courtesy of H. Kumada
Only Slow neutron reacts with boron

Fast neutron

Hydrogen, carbon

Cross-section of nuclear reaction

Neutron energy (eV)

Courtesy of H. Kumada
Only Slow neutron reacts with boron

Cross-section of nuclear reaction
- boron
- oxygen
- carbon

Neutron energy (eV)
\[ n + B(10) = Li + \alpha + \gamma \]

**Boron Neutron Capture Therapy**

**Physics**
- Neutron source
- Imaging

**Chemistry**
- Boron sources
- Encapsulation
- Vectorization

**Biology/medicine**
- Cellular studies
- Clinical trials and investigations

---

Collaborative work of different fields is essential
\[ n + B(10) = Li + \alpha + \gamma \]

**Main molecules used in BNCT**

**Requirements**
- millions of \(^{10}\text{B}\) near or inside cell \(\Rightarrow\) 20-35 \(\mu\text{g}^{10}\text{B}/\text{g}\)
- tumour-to-tissue ratio > 3
- low toxicity

**STELLA PHARMA CORPORATION (Japan) is the only drug company**

\(20 \text{ g}!!\)

**2.5 ~ 3.5 so far!!**

\(^{10}\text{B} (20\%)\)

\(^{11}\text{B} (80\%)\)

⇒ enrichment in \(^{10}\text{B}\)

**L-p-boronophenylalanine**

* \((L-BPA)\)*

**Sodium mercaptoundecahydrododecaborate**

* \((BSH)\)*

**Main issues**
- Not patentable \(\Rightarrow\) design of new boron-containing molecules and nanoparticles
- Well known \(\Rightarrow\) encapsulation and vectorization inside tumours
Mechanism of boron delivery to tumor cell through blood vessels

- **Blood Brain Barrier**
- **Tumor cell** (high amino acid metabolism)
- **Normal cell**

**BSH case** (brain tumor)

**BPA case** (skin cancer)

*Courtesy of H. Kumada*
Obstinate cancer therapy (brain cancer case)

Tumor cells invasion to normal brain zone

Main part of cancer

Malignant glioma:
- 3 months to live without therapy
- 12 months to live with standard therapy

Courtesy of H. Kumada
Obstinate cancer therapy (brain cancer case)

Tumor cells invasion to normal brain zone

Main part of cancer

Malignant glioma:
- 3 months to live without therapy
- 12 months to live with standard therapy

Courtesy of H. Kumada
Obstinate cancer therapy (brain cancer case)

Tumor cells invasion to normal brain zone

Normal zone

Main part of cancer

Malignant glioma:
- 3 months to live without therapy
- 12 months to live with standard therapy

Excision with surgery

Courtesy of H. Kumada
Main part of cancer

Tumor cells invasion to normal brain zone

Normal zone

Malignant glioma:
- 3 months to live without therapy
- 12 months to live with standard therapy

Obstinate cancer therapy (brain cancer case)

Brain cancer
- Excision with surgery
- Standard X-ray therapy

Courtesy of H. Kumada
Obstinate cancer therapy (brain cancer case)

Tumor cells invasion to normal brain zone

Main part of cancer

Normal zone

Malignant glioma:
- 3 months to live without therapy
- 12 months to live with standard therapy
Obstinate cancer therapy (brain cancer case)

Tumor cells invasion to normal brain zone

Main part of cancer

Normal zone

Malignant glioma:
- 3 months to live without therapy
- 12 months to live with standard therapy

Cell-level therapy is indispensable
Reactor-based BNCT facilities in the world

- **MITR** (1959～1999)
- **BMRR** (1951～1999)
- **RA-6** (2003～)
- **FiR-1** (1991～2011)
- **R2-0** (2001～2005)
- **HFR** (1997～)
- **Pavia** (2002～)
- **LVR-15** (2002～)
- **THOR** (2010～2011)
- **KUR** (1974～)
- **HTR**
- **JRR-3**
- **MHR**
- **JRR-2**
- **JRR-4**

By Hiroaki Kumada (Tsukuba Univ.)
Recent BNCT Facilities in Japan

Japan Atomic Energy Agency (JAEA)  
Japan Research Reactor No.4  
(Tokai Villa, Ibaraki)

University of Tsukuba

Kyoto Univ. Research Reactor Institute  
(KURRI) Research Reactor, KUR”(Osaka)

By Hiroaki Kumada (Tsukuba Univ.)
Reactor-based BNCT facilities in Japan

Reactor-based BNCT in Japan

- Reactor can be used only for clinical study.
- Reactor has to be stopped about a few months in a year for the inspection and maintenance by law.
- The number of the BNCT facilities was only two, and unfortunately JRR-4 has stopped by the huge earthquake in 2011.
- It is almost impossible to develop new reactor-based BCNT facility in Japan.

By Hiroaki Kumada (Tsukuba Univ.)
Methodology of accelerator-based neutron source design

Step 1: Protons are accelerated up to 2.5 ~ 30 MeV.
Step 2: Protons are injected to Li or Be target to produce neutrons.
Step 3: Fast neutrons are generated.
Step 4: Slow down fast neutrons by moderator to “BNCT epithermal” neutrons. (Step 4 is in common with a reactor-based BNCT)

Steps in designing of an accelerator-based neutron source for BNCT,
Step 1: We should choose the neutron production target material (Be or Li),
Step 2: Proton beam power can be decided from the necessary neutron flux for patient treatment,
Step 3: We choose accelerator technology by considering required proton energy and current.
1.2. Epithermal beam intensity

For the purposes of reporting beam intensity, the common definition for an epithermal energy range should be used, namely 0.5 eV to 10 keV. If other energy limits are used, they should be clearly reported.

Current experience shows that a desirable minimum beam intensity would be $10^9$ epithermal neutrons cm$^{-2}$ s$^{-1}$. Beams of $5 \times 10^8$ n cm$^{-2}$ s$^{-1}$ are useable, but result in rather long irradiation times.

Energy range of “BNCT epi-thermal” ➔ (0.5 eV ~ 10 keV)
Neutron flux ➔ $> 1 \times 10^9$ n/cm$^2$/s
1.3.1. The fast neutron component

In BNCT the energy range for fast neutrons is taken as $>10$ keV. Fast neutrons, which invariably accompany the incident beam, have a number of undesirable characteristics such as the production of high LET protons with a resulting energy dependence of their induced biological effects. Therefore, it is one of the main objectives of BNCT beam design to reduce the fast neutron component of the incident beam as much as possible.

Another major objective is clearly to have as high an epithermal flux as possible. In existing facilities the range of dose from this component is from $2.5$ to $13 \times 10^{-13}$ Gy cm$^2$ per epithermal neutron. A target number should be $2 \times 10^{-13}$ Gy cm$^2$ per epithermal neutron.

1.3.2. The gamma ray component

Because of the energy range of the gamma radiation, it results in an non-selective dose to both tumour tissue and a large volume of healthy tissue. Hence it is desirable to remove as much gamma radiation from the beam as possible. Since there are also $(n,\gamma)$ reactions occurring inside the patient, the importance of this component in the incident beam is somewhat reduced. Nevertheless, a target number for this should be $2 \times 10^{-13}$ Gy cm$^2$ per epithermal neutron. The range in existing facilities is from $1$ to $13 \times 10^{-13}$ Gy cm$^2$ per epithermal neutron.
Comparison between Lithium and Beryllium

\[ ^7\text{Li}(p,n)^7\text{Be} \quad ^9\text{Be}(p,n)^9\text{B} \]

From the cross section viewpoint, Lithium is very attractive in the low primary proton energy region.

Primary proton energy (MeV)

Normalized neutron yield \( (n/\mu \text{ coulomb}) \)

by Y. Kiyanaogi

H. Tanaka, Kyoto Univ. Research Reactor Institute
Neutron energy spectrum of lithium and beryllium for various production angle (by Yoshiaki Kiyanagi)

Neutron yield (n/mA/s/keV)

Lithium target

Beryllium target

Neutron yield (n/mA/s/sr)

Low neutron energy

Forward angle

Primary Proton Energy

30 MeV

Primary Proton Energy

8 MeV
### Criteria of the technology choice

<table>
<thead>
<tr>
<th>Target</th>
<th>Proton Energy</th>
<th>Problems to be solved</th>
</tr>
</thead>
</table>
| **Solid Lithium** | *7Li*(p,n)*7Be* | 2.5~3 MeV  
- Low melting point (180.5 °C)  
  → heavy target heat load must be cooled effectively to avoid evaporation  
- Generation of *7Be* (radioactive nuclide with half-life of 53 days)  
- Generation of tritium by reaction of *6Li*(n,t)*4He* → *6Li*/*7Li* (7.59/92.41%)  
- Vigorous reaction with water and easy-oxidization |
| **Liquid Lithium** |              |  
- Generation of *7Be* and Tritium (same as above).  
- Need to handle liquid metal in a hospital cautiously. |
| **Beryllium**   | *9Be*(p,n)*9B* | > 13 MeV  
- High energy neutrons produce many kind of active nuclides.  
  → Heavy residual radiation (> 100 mSv/h)  
- High energy neutrons may give damages to healthy tissues (need more study). |
|               | < 13 MeV      |  
- Lower yield  
  → Need to develop a high current accelerator.  
- Heavy target heat load must be cooled efficiently.  
- Avoid target damage by blistering  
  (Blistering: stopped proton in the metal easily capture free electrons and generate hydrogen in the target → flaking/peeling takes place). |
<table>
<thead>
<tr>
<th>Location</th>
<th>Machine (Status)</th>
<th>Target &amp; reaction</th>
<th>Beam Energy (MeV)</th>
<th>Beam current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budker Institute (Russia)</td>
<td>Vacuum insulated Tandem (Ready)</td>
<td>Solid $^7$Li(p, n)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>iPPE-Obninsk (Russia)</td>
<td>Cascade generator KG- 2.5 (Ready)</td>
<td>Solid $^7$Li(p, n)</td>
<td>2.3</td>
<td>3</td>
</tr>
<tr>
<td>Birmingham Univ. (UK)</td>
<td>Dynamitron (Ready)</td>
<td>Solid $^7$Li(p, n)</td>
<td>2.8</td>
<td>1</td>
</tr>
<tr>
<td>Soreq (Israel)</td>
<td>RFQ-DTL (Ready)</td>
<td>Liquid $^7$Li(p, n)</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Legnaro INFN (Italy)</td>
<td>RFQ</td>
<td>Be(p, n)</td>
<td>4-5</td>
<td>30</td>
</tr>
<tr>
<td>CNEA Buenos Aires (Argentina)</td>
<td>Single ended Tandem Electrostatic Quadrupole (TESQ)</td>
<td>Be(d, n)</td>
<td>1.4</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solid $^7$Li(p, n)</td>
<td>2.5</td>
<td>30</td>
</tr>
<tr>
<td>KURRI</td>
<td>Cyclotron (Clinical Trial)</td>
<td>Be(p, n)</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>University of Tsukuba</td>
<td>RFQ-DTL</td>
<td>Be(p, n)</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>NCCenter, CICS</td>
<td>RFQ</td>
<td>Solid $^7$Li(p, n)</td>
<td>2.5</td>
<td>20</td>
</tr>
<tr>
<td>Fukushima South Tohoku Hospital</td>
<td>Cyclotron</td>
<td>Be(p, n)</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>Osaka University</td>
<td>Neutron target system only</td>
<td>Liquid $^7$Li(p, n)</td>
<td>~2.5</td>
<td>-</td>
</tr>
<tr>
<td>Nagoya University</td>
<td>Dynamitron</td>
<td>Solid $^7$Li(p, n)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planning and designing : OIST (Okinawa), Osaka Medical College (Osaka), Edogawa Hospital (Tokyo)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

By Hiroaki Kumada (Tsukuba Univ.)
In Japan, many institutes and hospitals are developing an accelerator-based BNCT facility, in which most combinations of accelerator and target technologies are included. As a typical example of these technologies, I will show following six cases.

<table>
<thead>
<tr>
<th>Group</th>
<th>Accelerator</th>
<th>Beam Energy</th>
<th>Power</th>
<th>Target material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Kyoto University</td>
<td>Cyclotron</td>
<td>30 MeV</td>
<td>33 kW</td>
<td>Thick beryllium (5.5 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Clinical trial</strong></td>
</tr>
<tr>
<td>2. National Cancer Center</td>
<td>CW RFQ</td>
<td>2.5 MeV</td>
<td>50 kW</td>
<td>Solid lithium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Passed radiation facility inspection</strong></td>
</tr>
<tr>
<td>3. Nagoya University</td>
<td>Dynamitron</td>
<td>2.8 MeV</td>
<td>50 kW</td>
<td>Hermetic liquid lithium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Accelerator commissioning and target development phase</strong></td>
</tr>
<tr>
<td>4. Tokyo Institute of Technology</td>
<td>-----------</td>
<td>-----------</td>
<td>--------</td>
<td>Liquid lithium target</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Target development only</strong></td>
</tr>
<tr>
<td>5. Tsukuba University</td>
<td>Pulsed RFQ + DTL</td>
<td>8.0 MeV</td>
<td>80 kW</td>
<td>Thin beryllium (0.5 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Accelerator commissioning</strong></td>
</tr>
<tr>
<td>6. OIST</td>
<td>Pulsed RFQ</td>
<td>3.0 MeV</td>
<td>30 kW</td>
<td>Solid lithium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Design phase based on new solid lithium target technology</strong></td>
</tr>
</tbody>
</table>
Technology-1:

30 MeV, 1.1 mA (33 kW) cyclotron + beryllium target

Kyoto University & Sumitomo Heavy Industries, Ltd.

The most advanced group and in clinical trial phase

Characteristics:
- Cyclotron is a mature technology
- 5.5 mm thick target ➔ no risk on the target manufacturing technology
- Proton beam stops in water ➔ free from the blistering problem

Photos and the figures are by Motoki Tanaka (Kyoto University)
Risk:

- High residual radioactivity

By Motoki Tanaka (Kyoto University)
Technology-2: 2.5 MeV, 20 mA (50 kW) RFQ (CW) + solid lithium target

National Cancer Center & CICS, Inc.

Passed the radiation facility safety inspection in March 2016

Characteristics:
- Low risk for CW RFQ linac operation
- Simple moderator design and structure

Risk:
- Complex target design, structure and operation
How to avoid concentration/accumulation of $^7$Be.

Three rotating units are used

① Port 1: irradiation port
② Port 2: wash out port
  ➢ (utilizing that lithium reacts with water actively)
  ➢ Lithium target layer can be washed out with water before accumulating $^7$Be frequently and waste liquid is stored in a tank.
③ Port 3: vapor deposition port
  ➢ New lithium layer is developed on the heat sink with vapor deposition method.

The photo and drawings are from Home Page Of National Cancer Center, CICS and paper by Linac Systems INC.
Figure 1: Protons (1) strike a 50-μm lithium metal layer (2) that is deposited on a Pd anti-blotting substrate (3), supported by a channelized conical heat exchanger (4). Coolant (5) flows through a conical-annular duct that encompasses the channels of the heat exchanger; reverses at the apex; returns via an outer conical-annular duct, and exits (6).

Figure 4: Manifold with target heat exchanger installed.

Issues
① Layer thickness control is difficult.
② Storage of waste liquid is troublesome.

===Unsealed Radioactive material====
**Technology-3: NUANS**

2.8 MeV, 15 mA (42 kW) Dynamitron + solid lithium target

Nagoya University & YAGAMI Co., Ltd.

- Accelerator commissioning
- Target development

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**Lithium Target and moderator**

Phantom

Titanium thin foil is used as a cover to prevent evaporation or oxidization

===sealed radioactive material===

Cooling water channel

Ti-foil cover

Li-7 (99%), 140 μm

target base plate (Ta/Fe)

Figures: by Yoshiaki Kiyanagi of Nagoya University

page23
(1) Ta backing plate is connected to a Cu cooling base by HIP process*. The emboss-structure is prepared on the surface of Ta plate.

- Ta: High threshold for blistering (H\(^+\) fluence > 1.6 \times 10^{21} \text{H}^+/\text{cm}^2)
- High corrosion resistance and good wettability for liquid Lithium

*HIP: Hot Isostatic Press

Courtesy of Y. Kiyanagi
Cross sectional view of the Compact Sealed Li target

(1) Ta backing plate is connected to a Cu cooling base by HIP process*. The emboss-structure is prepared on the surface of Ta plate.

Ta : High threshold for blistering (H⁺ fluence > 1.6 x 10²¹ H⁺/cm²)
High corrosion resistance and good wettability for liquid Lithium

(2) Thin Ti foil is jointed to the Ta plate by Hot press process.
Ti : High corrosion resistance and good wettability for liquid Lithium

*HIP : Hot Isostatic Press

Courtesy of Y. Kiyanagi
Cross sectional view of the Compact Sealed Li target

(1) Ta backing plate is connected to a Cu cooling base by HIP process*. The emboss-structure is prepared on the surface of Ta plate.
   Ta: High threshold for blistering (H\(^+\) fluence > 1.6 \(\times\) 10\(^{21}\) H\(^+/\)cm\(^2\))
   High corrosion resistance and good wettability for liquid Lithium

(2) Thin Ti foil is jointed to the Ta plate by Hot press process.
   Ti: High corrosion resistance and good wettability for liquid Lithium

(3) Li is set in the thin space of the emboss structure.

![Cross-sectional view of the Compact Sealed Li target](image)

*HIP: Hot Isostatic Press

**Courtesy of Y. Kiyanagi**
Cross sectional view of the Compact Sealed Li target

Completed

(1) Ta backing plate is connected to a Cu cooling base by HIP process*. The emboss-structure is prepared on the surface of Ta plate.

Ta: High threshold for blistering (H⁺ fluence > 1.6 x 10²¹ H⁺/cm²)
High corrosion resistance and good wettability for liquid Lithium

(2) Thin Ti foil is jointed to the Ta plate by Hot press process.

Ti: High corrosion resistance and good wettability for liquid Lithium

(3) Li is set in the thin space of the emboss structure.

← Under development

(4) Proton beam is irradiate to the Li through the Ti foil.

Li and Be-7 can be confined in the target by the Ti foil.

Proton Beam (>2.8MeV, 42kW)

Power density: 6.6 MW/m²
(Irradiation area = 80 x 80 mm²)

Ti or Be foil (t ~ 10 µm)
Li layer (t ~ 0.14mm)
Cooling water
Cu base (130 x 130 mm)
Ta backing plate

 Courtesy of Y. Kiyanagi

*HIP: Hot Isostatic Press
Beam shaping assembly

![Diagram of beam shaping assembly](image)

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>Improved</th>
<th>Total weight: 5.46 t</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{epi}} \times 10^9 \text{n/cm}^2/\text{s}$</td>
<td>0.78</td>
<td>1.89</td>
<td>$\geq 1$ Epi-thermal</td>
</tr>
<tr>
<td>$D_f \times 10^{-13} \text{Gy} \cdot \text{cm}^2$</td>
<td>1.99</td>
<td>1.99</td>
<td>$\leq 2$ Fast neutron rate</td>
</tr>
<tr>
<td>$D_g \times 10^{-13} \text{Gy} \cdot \text{cm}^2$</td>
<td>1.79</td>
<td>1.69</td>
<td>$\leq 2$ $\gamma$ ray rate</td>
</tr>
<tr>
<td>$N_{t/e}$</td>
<td>0.036</td>
<td>0.047</td>
<td>$\leq 0.05$ Thermal neutron rate</td>
</tr>
<tr>
<td>$C/F$</td>
<td>0.785</td>
<td>0.704</td>
<td>$\geq 0.7$ Current/Flux</td>
</tr>
</tbody>
</table>

Energy spectra at a exit

- **Dynamitron中性子源**
- BSA01
- BSA05

![Energy spectra graph](image)
Technology-4:
Liquid lithium target development
Tokyo Institute of Technology & SUKEGAWA ELECTRIC CO., Ltd.
• Verification test only

Liquid lithium flow is successfully realized
Temperature 220 º C
Flow speed 30 m/s
Vacuum pressure 10^{-4} Pa
Layer width 45 ~ 50 mm
Length 50 mm
Liq. Li circulation electromagnetic pump

Figures: Home page of Tokyo Institute of Technology
Ibaraki-BNCT

Accelerator Parameter:
- Energy: 8 MeV
- Peak beam current: 50 mA (max)
- Beam pulse width: 1 ms (max)
- Repetition rate: 200 Hz (max)
- Duty: 20 % (max)
- Ion source: 50 keV ECR + Low Energy Beam Transport

Characteristics:
- J-PARC design base: RF frequency 324 MHz
- Pulsed linac
- High peak current: ECR ion source (pulse operation) with 60 mA peak current
- Long pulse width and high repetition rate: innovative water cooling system

New developments in the linac system:
- Long pulse and high duty klystron modulator power supply
  ➔ KEK + DAWONSYS CO., LTD. (Korea)
- Cooling water system for high duty RFQ and DTL with a large temperature difference (ΔT=10 °C) and dynamic temperature control ➔ KEK and MHI
Existing building is used after remodeling
- Limited space ➔ Single klystron
- Room layout ➔ Complex beam transport
Why 8 MeV?
- Neutron energy < 6 MeV
- Below threshold energy of many nuclear reaction channels
Target and moderator development

Technology-5 (continued):

Diffusion bonding with hot isostatic pressing (HIP)

Air
Beryllium
Hydrogen storage metal
Copper (Heat sink)

0.5 0.5mm

Diffusion bonding with hot isostatic pressing (HIP)

Fast Neutron Filter
Moderator
Collimator
Beam Port

Beryllium
Target

Proton Beam

Shield

Thermal neutron filter
γ-ray shield

Simulation: \(4.66 \times 10^9\) n/s/cm²
Design of OIST-BNCT frontend based on solid lithium target

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>3 MeV</td>
</tr>
<tr>
<td>Max. peak current</td>
<td>50 mA</td>
</tr>
<tr>
<td>Beam pulse width</td>
<td>0.1 ~ 1 ms</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>SS, 1 ~ 200 Hz</td>
</tr>
<tr>
<td>Max. duty</td>
<td>20%</td>
</tr>
<tr>
<td>Max. power</td>
<td>30 kW</td>
</tr>
</tbody>
</table>

Subsystem (red frame only)
1. 50kV-ECR ion source → Ibaraki type
2. Low Energy Beam Transport
3. 352MHz RFQ → New, higher than Ibaraki
4. Multi-beam Klystron → New
   600 kW, 352 MHz
5. Klystron modulator → Ibaraki type but lower HV
   HV < 35 kV
   Capacitor Charging PS
   Droop Compensation circuit
6. Cooling water system → Ibaraki type

Require more consideration
1. Larger size solid lithium target manufacturing (50mm so far)
2. Neutron moderator design → learn from Nagoya

Technology-6:
3 MeV, 10 mA (30 kW) RFQ linac + solid lithium target

OIST
• Design phase
50 keV ECR ion source

Low Energy Beam Transport

3 MeV RFQ (352MHz)

Cryopump

MBK

Circulator

DTL (+7MeV)---Option

Frontend: RED FRAME ONLY

RED FRAME ONLY

MBK

Circulator

Cryopump

50 keV ECR ion source

3 MeV RFQ (352MHz)

Frontend: RED FRAME ONLY

RED FRAME ONLY

MBK

Circulator

Cryopump

50 keV ECR ion source

3 MeV RFQ (352MHz)
Innovative solid lithium target
development by
ULVAC, Inc. and SANKI INDUSTRY
----- Stable and tractable -----

Bonding a thin solid lithium plate on copper heat sink in the glow box (left photo)
----- Good thermal contact at the layer boundary and special water flow channel structure to make an effective heat removal are realized by -----
① Layer boundary is cleaned up before bonding
② Copper heat sink structure
③ Lithium surface is covered with stable thin film (a few micron)
===sealed radioactive material===

Courtesy of ULVAC, Inc and SANKI INDUSTRY, Inc.
Irradiation experiment with the DC accelerator (right figure)

- Beam energy 3MeV,
- Beam current (DC) 60 μA,
- Beam spot diameter 5 mm

No damage by blistering, no evaporation of lithium

Equivalent to 34 mA average current for 120 mm target and beam spot diameter.
Summary and conclusion,
my personal view

Various technology choice

<table>
<thead>
<tr>
<th>Group</th>
<th>Accelerator</th>
<th>Beam Energy</th>
<th>Power</th>
<th>Target material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Kyoto University</td>
<td>Cyclotron</td>
<td>30 MeV</td>
<td>33 kW</td>
<td>Thick beryllium (5.5 mm)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>==Clinical trial==</td>
</tr>
<tr>
<td>2. National Cancer Center</td>
<td>CW RFQ</td>
<td>2.5 MeV</td>
<td>50 kW</td>
<td>Solid lithium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>==Passed radiation facility inspection==</td>
</tr>
<tr>
<td>3. Nagoya University</td>
<td>Dynamitron</td>
<td>2.8 MeV</td>
<td>50 kW</td>
<td>Hermetic liquid lithium</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>==Accelerator commissioning and target development phase==</td>
</tr>
<tr>
<td>4. Tokyo Institute of Technology</td>
<td>------------</td>
<td>---------</td>
<td>-------</td>
<td>Liquid lithium target</td>
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<td>==Target development only==</td>
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<tr>
<td>5. Tsukuba University</td>
<td>Pulsed RFQ + DTL</td>
<td>8.0 MeV</td>
<td>80 kW</td>
<td>Thin beryllium (0.5 mm)</td>
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<td></td>
<td></td>
<td>==Accelerator commissioning==</td>
</tr>
<tr>
<td>6. OIST</td>
<td>Pulsed RFQ</td>
<td>3.0 MeV</td>
<td>30 kW</td>
<td>Solid lithium</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>==Design phase based on new solid lithium target technology==</td>
</tr>
</tbody>
</table>
1. The most advanced project in Japan is the group-1 (Kyoto University). Southern TOHOKU General Hospital in Fukushima, Japan has already constructed the same type and ready for the clinical trial. A few more hospitals are going to introduce the same type.

2. It should be mentioned that we still need more studies and experiences to establish the real mass production type for the wide application.

3. We should not forget that the accelerator and target are the only frontend of the facility.

4. Important development items are the better drag delivery system, the method of clinical treatment planning including imaging technology and understanding of cancer mechanism.