

Neutron sources for BNCT treatment facilities

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*IAEA, Technical Meeting on Advances in BNCT
July 27-30, Vienna, Austria and the rest of the world.*



TECDOC1223 (2001)

- **2.6. Accelerators**

An accelerator would be a useful NCT neutron source in a hospital for several reasons.

First, accelerators are much more acceptable to the public than reactors.

Second, it generally involves fewer complications with respect to licensing, accountability and disposal of nuclear fuel. It can also be switched on and off.

However, it must be recognized that the technology is not yet proven.

The radiofrequency quadrupole (RFQ) accelerator is considered as the most promising method. The RFQ can be used to generate a high current of protons with an energy slightly higher than the threshold (1.88 MeV) for the ${}^7\text{Li}(\text{p},\text{n}){}^7\text{Be}$ reaction.

The resulting neutrons generally require less moderation than those from a reactor.

Outline/relevant issues

- **Nuclear reactions and accelerators.**
- **Low-energy Accelerator-Based BNCT programs worldwide. Some comparisons.**
- **Targets & Beam Shaping Assemblies (BSA).**
- **Accelerator-Based BNCT programs worldwide. Emphasis on Japanese programs.**
- **Conclusions/remarks.**



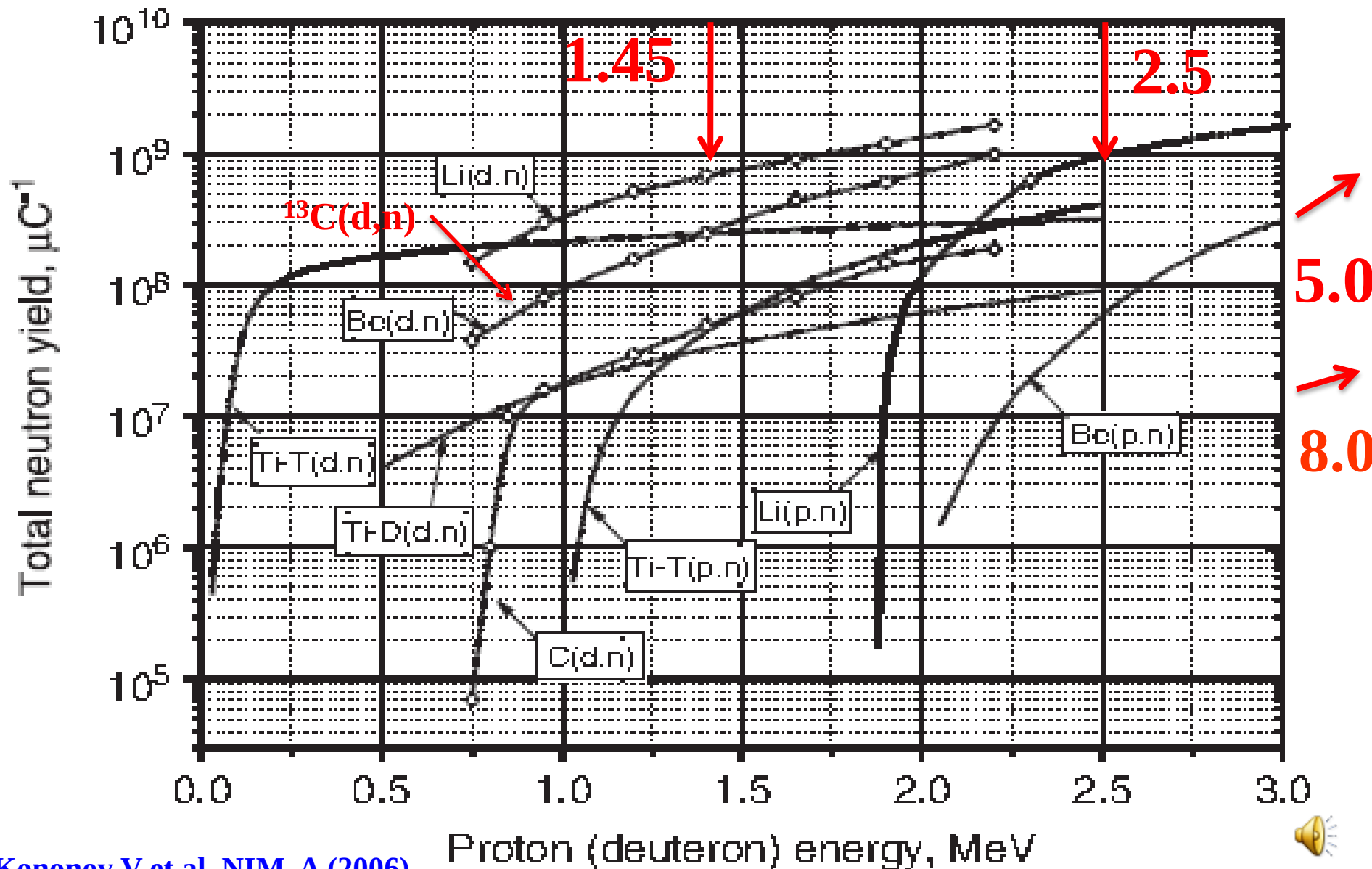
In-hospital AB-BNCT

Criteria for “**best**” solutions and for widest possible dissemination:

- **Safety (e.g., lowest activation of facility, no potentially hazardous materials).**
- **Simplicity-Reliability (smallest number of ancillary systems, e.g. no SF6, ease of maintenance).**
- **Lowest possible cost (smallest accelerator and simplest possible technologies).**



Neutron producing reactions



Nuclear reactions & material properties

Reaction	E _{thres} (MeV)	Radioactive products	Melting T (°C)	Therm cond (W/m-K)
${}^7\text{Li}(\text{p},\text{n}){}^7\text{Be}$	1.88	Yes	180	84.7
${}^9\text{Be}(\text{p},\text{n}){}^9\text{B}$	2.06	No ^a	1287	201
${}^9\text{Be}(\text{d},\text{n}){}^{10}\text{B}$	0 (exoergic)	No	1287	201
${}^9\text{Be}(\text{d},\text{n}){}^{10}\text{B}^*$	$\approx 1.0^{\text{b}}$	No	1287	201
${}^{13}\text{C}(\text{d},\text{n}){}^{14}\text{N}^{\text{c}}$	0	No	3550	230

^aVery short lived activity with no gamma emission.

^b Strong population of an excited state at ≈ 5.1 MeV in ${}^{10}\text{B}$. The reaction for population of this states has an effective threshold of ≈ 1 MeV. 69% of neutrons produced have energies below 1 MeV.

^c 70% of neutrons produced have energies below 1 MeV.

Reminder: Coulomb barriers of protons on common structural materials, Fe and Cu ≈ 5 MeV. Activation threshold for neutrons ≈ 6 MeV. 

Active low-energy AB-BNCT programs worldwide (not exhaustive)

1. Japan: Tsukuba, Nat. Cancer Center-Tokyo, Nagoya, Okinawa,..
2. Russia: Budker Institute Nuclear Physics, Novosibirsk.
3. Finland: Helsinki University Central Hosp.-NTI, Helsinki.
4. Argentina: CNEA, Buenos Aires.
5. Israel: SARAF, Soreq.
6. Italy: INFN-CNAO, Legnaro & Pavia.
7. China: Xiamen Humanity Hospital. Xiamen. TAE Life Sciences.
8. Korea: LINAC-based Dawonsys A-BNCT (10 MeV, commissioning phase) + KIRAMS-CNEA-Collaboration.
9. UK : Birmingham.



Accelerators/facilities for BNCT worldwide

Location	Machine /Facility Status/Final power	Target & reaction	Beam energy (MeV) % Neutron yield at $0^\circ < 1$ (MeV)	Int. goal Actual (mA)
Budker Institut, Novosibirsk Russia	Vacuum insulated Tandem. Developed. 23 kW.	Solid ${}^7\text{Li}(\text{p},\text{n})$	2.0 - 2.3 100% < 1 MeV	10 9
Tsukuba Japan	RFQ-DTL. Under development. 80 kW	thick 0.5mm $\text{Be}(\text{p},\text{n})$	8 21% < 1MeV	10 (> 5) 2
HUCH-NTI Helsinki Finland	Single-ended. DC. Commissioning. 78 kW.	Solid ${}^7\text{Li}(\text{p},\text{n})$	2.6 100% < 1 MeV	+30 +30
CNEA Buenos Aires Argentina	Single-ended ESQ. Under development & construction. 43.5 kW	${}^9\text{Be}(\text{d},\text{n})$ thin ${}^{13}\text{C}(\text{d},\text{n})$ thick	1.45 69±3% < 1 MeV 70% < 1 MeV	30 7
NCCenter- CICS Tokyo, Japan	RFQ. Clinical Trial. 50 kW.	Solid ${}^7\text{Li}(\text{p},\text{n})$	2.5 100% < 1 MeV	20 12
Nagoya Univ. Japan	Dynamitron. DC. Commissioning. 42 kW.	Solid ${}^7\text{Li}(\text{p},\text{n})$	2.8 95% < 1 MeV	15 4
Soreq Israel	RFQ-DTL. Under development. 50 kW	Liquid (jet) ${}^7\text{Li}(\text{p},\text{n})$	2.5 100% < 1 MeV	20 2
INFN-CNAO Legnaro-Pavia Italy	RFQ-DTL. Under development.100 kW.	$\text{Be}(\text{p},\text{n})$	5 34% <1 MeV	20-30 ?
Xiamen Humanity Hosp. China	Vacuum insulated Tandem. 25 kW.	Solid ${}^7\text{Li}(\text{p},\text{n})$	2.5 100% < 1 MeV	10 ?



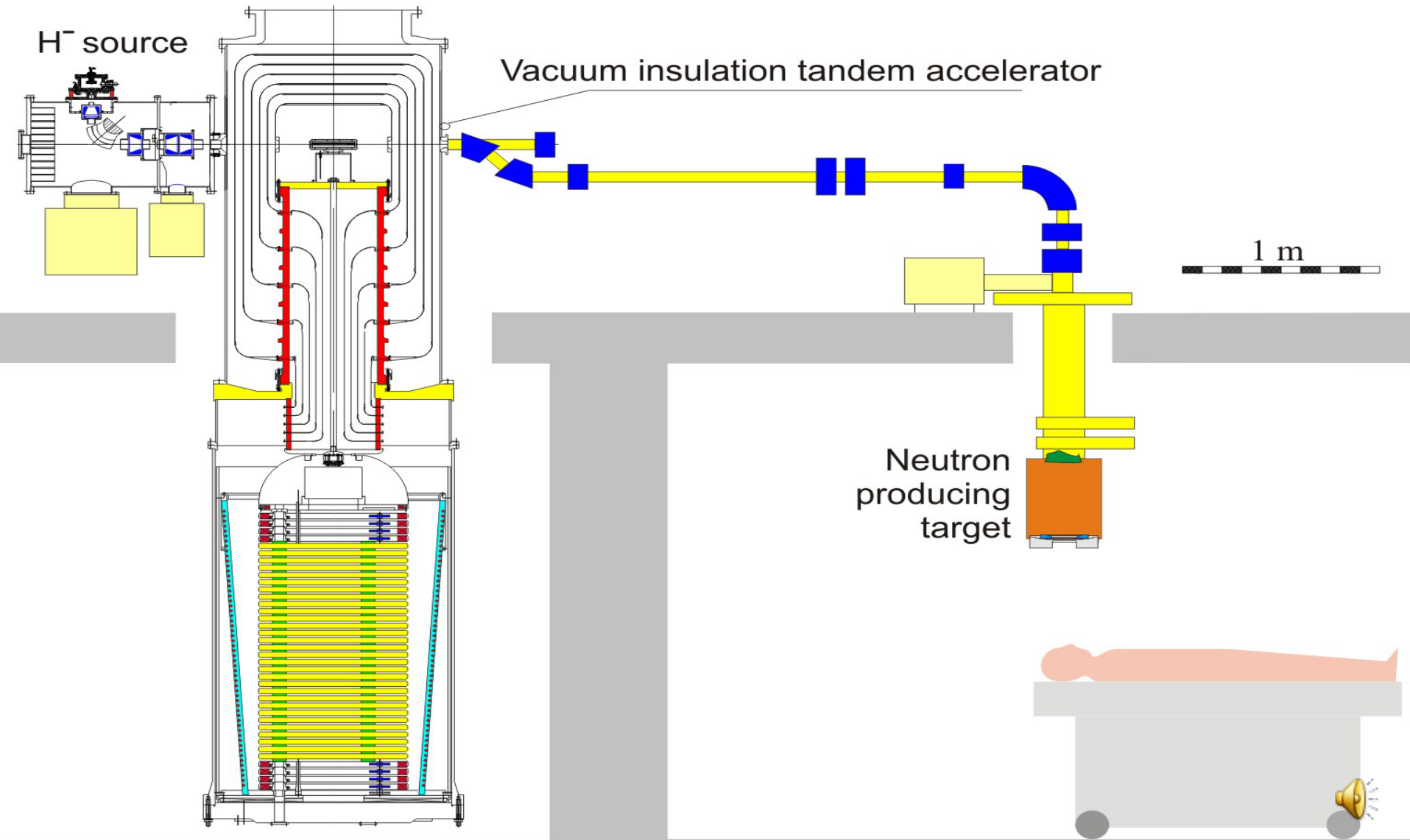
Two technologies

- **1. Electrostatic (ES):**
Vacuum insulated Tandem,
Electrostatic Quadrupole (ESQ),
Single-ended DC,
Dynamitron
- **2. Radiofrequency (RF)**



BINP Vacuum Insulated Tandem(VITA)

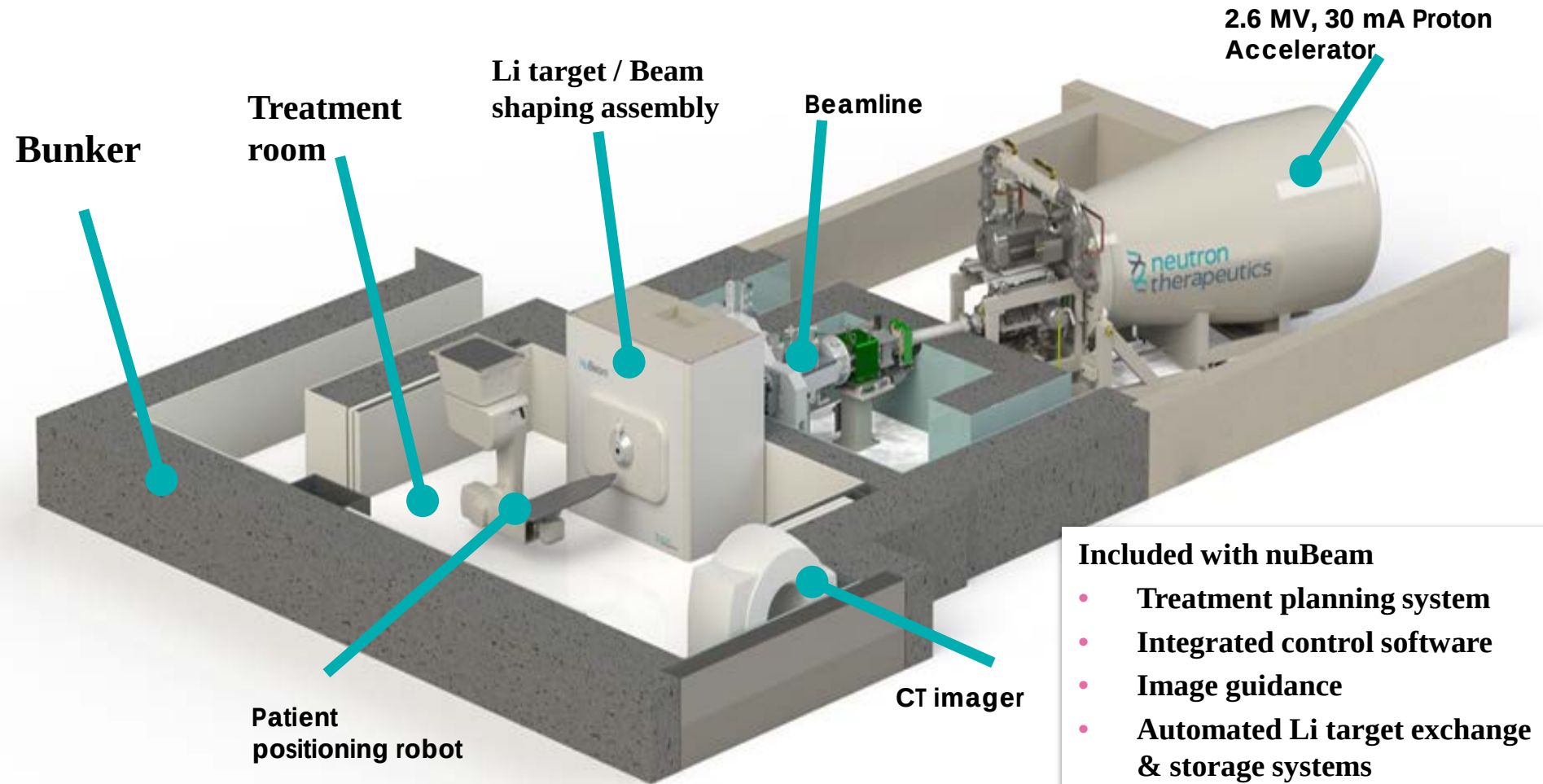
(S.Taskaev et al.)



Helsinki Central University Hospital (Porra et al.)



ACCELERATOR BASED BNCT SOURCE



0.72 MV ESQ in-air
completed (Argentina)



**Accelerator development
lab and future BNCT
treatment Centre.
Kreiner et al.**



Nagoya Dynamitron (2.8 MeV)

Kiyanagi et al., Yoshihashi et al.



Two technologies

- **1. Electrostatic (ES)**
- **2. Radiofrequency (RF): very high precision machining, RF power generation tech.
RF Quadrupole (RFQ),
Drift Tube LINAC (DTL)**



Tsukuba University (Ibaraki) Kumada et al.

- RFQ + DTL
- 8 MeV proton beam; 5 mA (goal), actual (few mA).
- Be target. ${}^9\text{Be}(p,n){}^9\text{B}$ reaction
- 6.1 MeV max. neutron energy. $\langle E_n \rangle \approx 1.7 \text{ MeV}$.

National Cancer Center (Tokyo) Nakamura et al

- RFQ (Accsys Inc.)
- 2.5 MeV protons; 20 mA
- Solid ${}^7\text{Li}(p,n)$
- Clinical trial

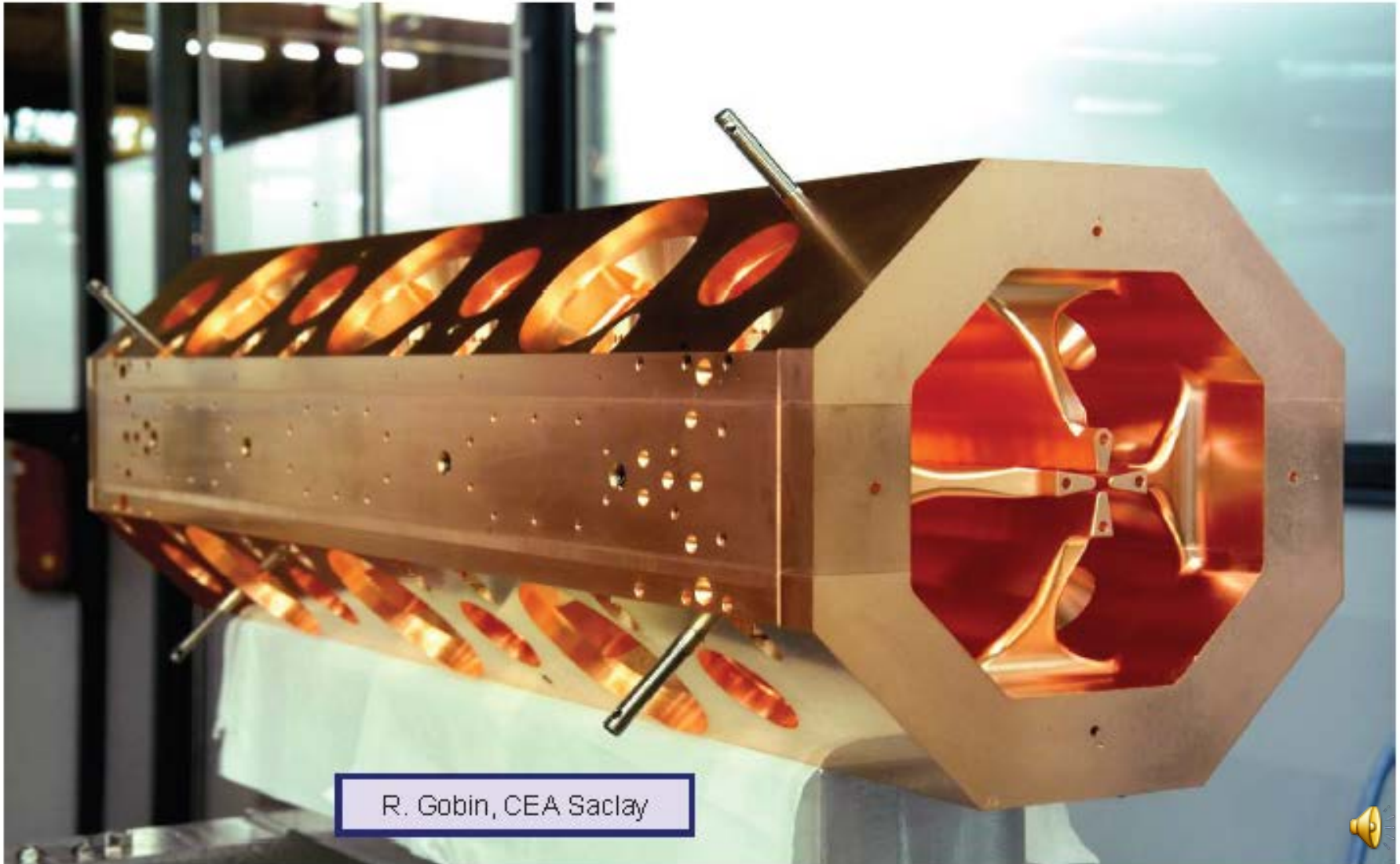
Legnaro-Pavia-CNAO Altieri-Rossi

- RFQ + DTL, 5 MeV protons; 20 mA
- Be (p,n)



RFQ- Radiofrequency Quadrupole

RFQ Herstellung



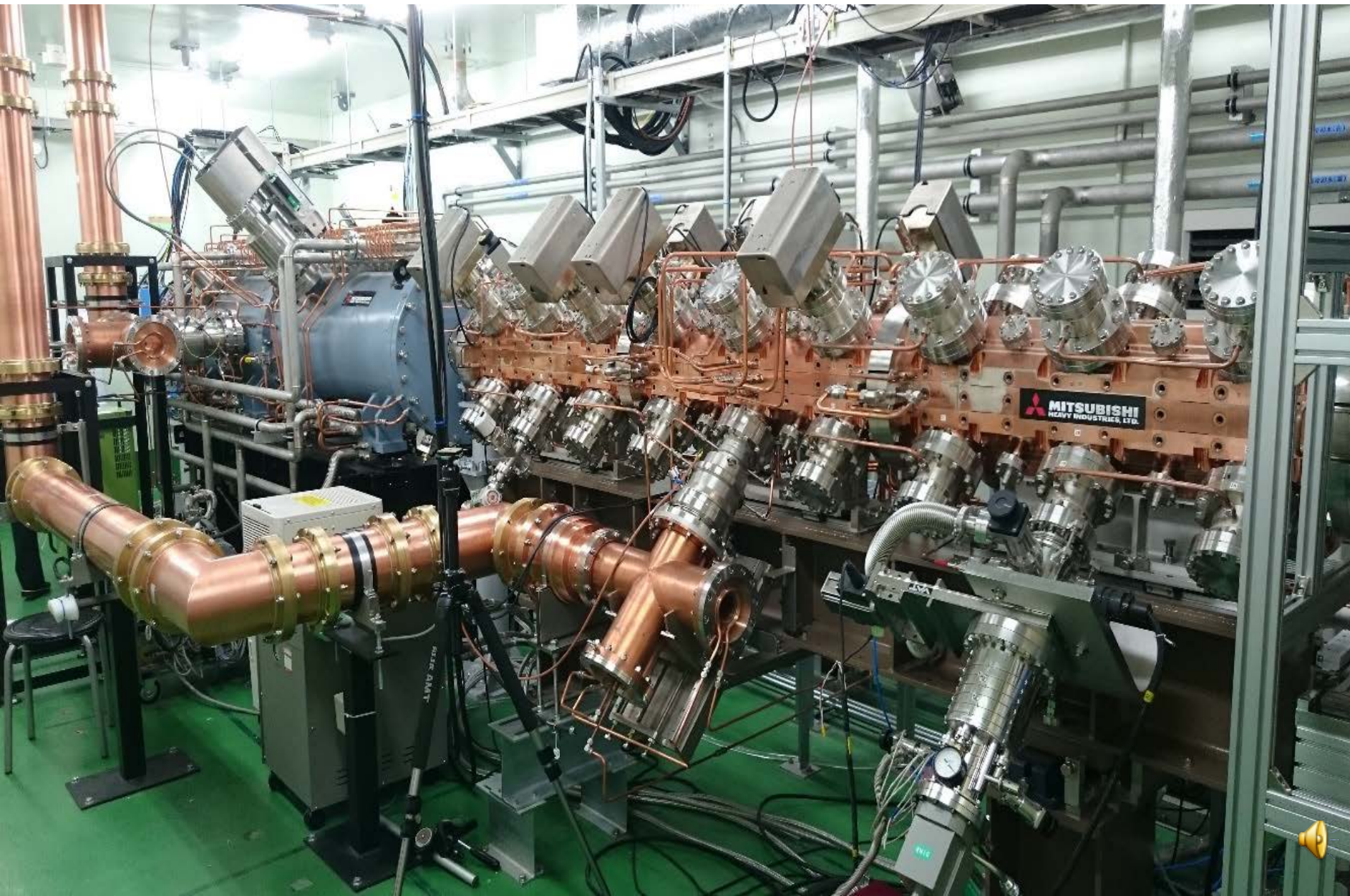
R. Gobin, CEA Saclay



Drift Tube LINAC (DTL)



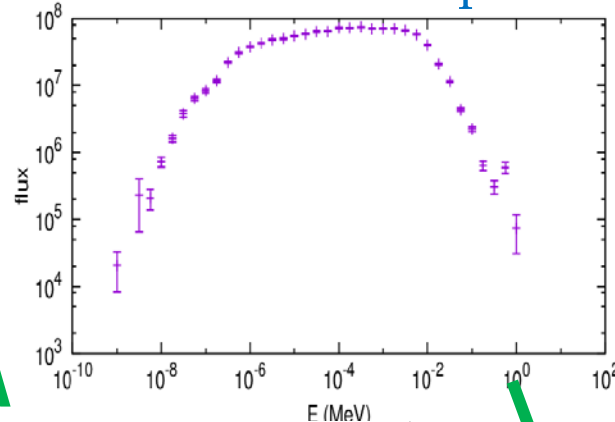
Ibaraki prefecture RFQ + DTL



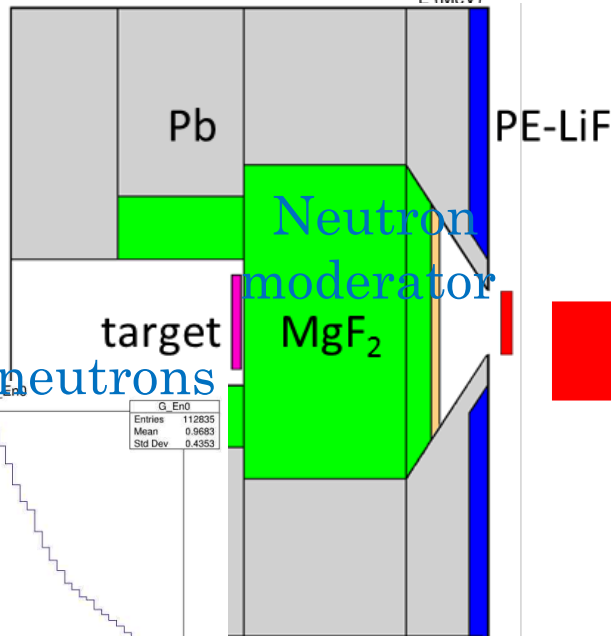
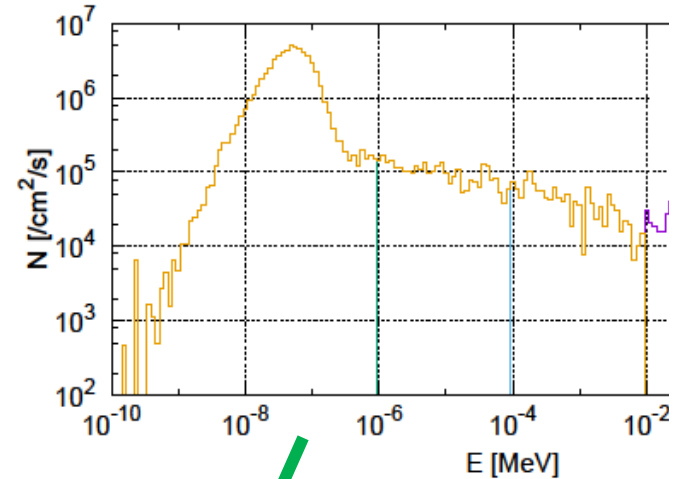
Beam Shaping Assembly (BSA)

(Neutrons are moderated from around a few 10s MeV to epithermal energy (0.5eV~10keV))

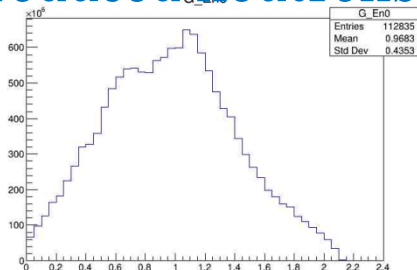
Epithermal neutron spectrum



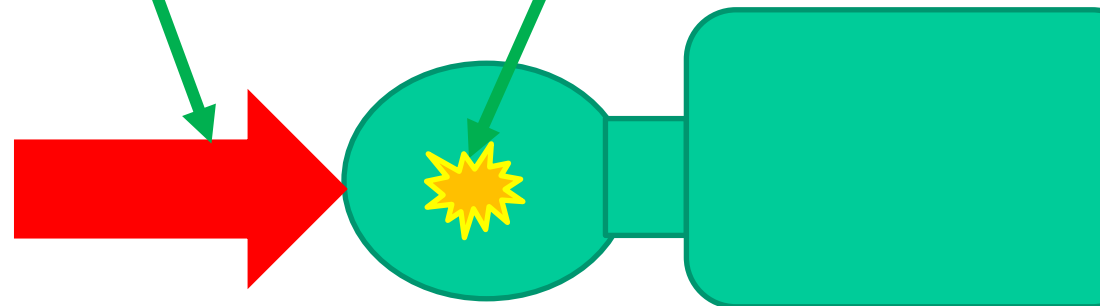
Thermal neutron spectrum



Produced neutrons



Up to few 10s MeV or sub-MeV

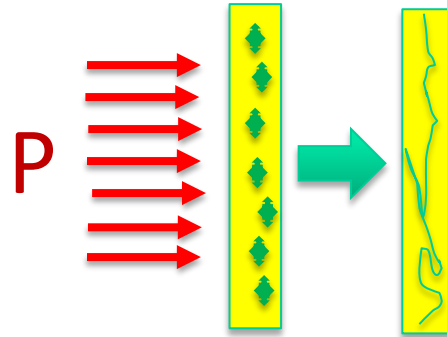


To treat cancer at deep position, epithermal neutrons are injected, and they become thermal neutrons near the tumor.

Neutron targets

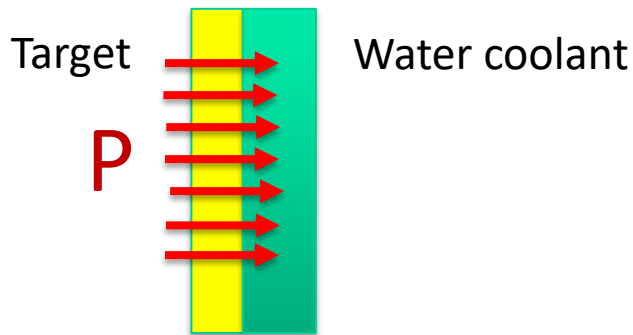
Issue at a low proton energy: Blistering

Hydrogen accumulates at almost the same position, and then will break the target. It may decide life of the target.



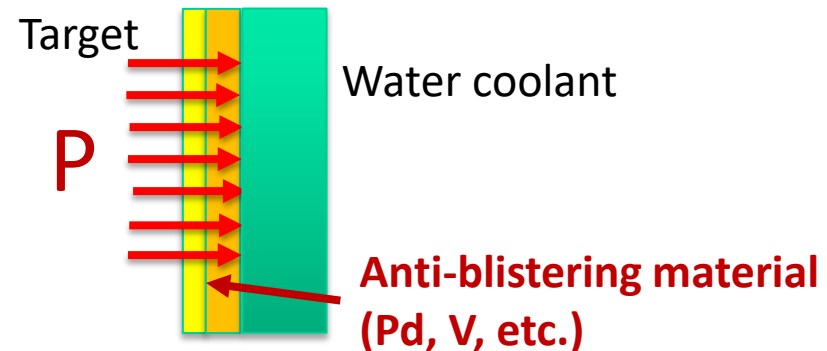
Y. Kiyanagi, TRO, 2:55 (2018).
doi: 10.21037/tro.2018.10.05

At high proton energy
Thick target=structure material



Protons directly enter coolant water.
Easy to handle. 30MeV p-accelerator

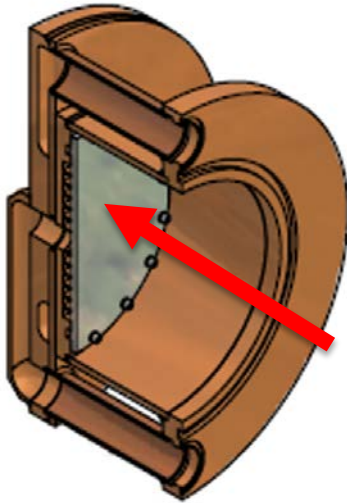
At low proton energy
Thin target



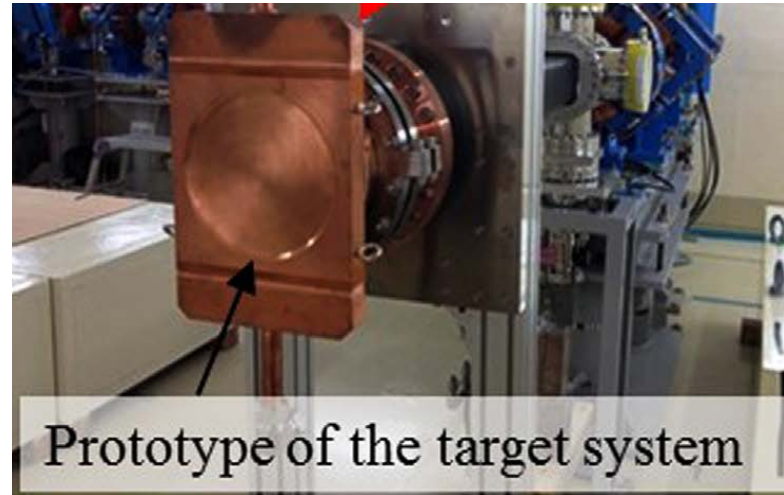
Protons should be maintained in hydrogen absorber (Pd, etc.). Complicated structure.

Be targets

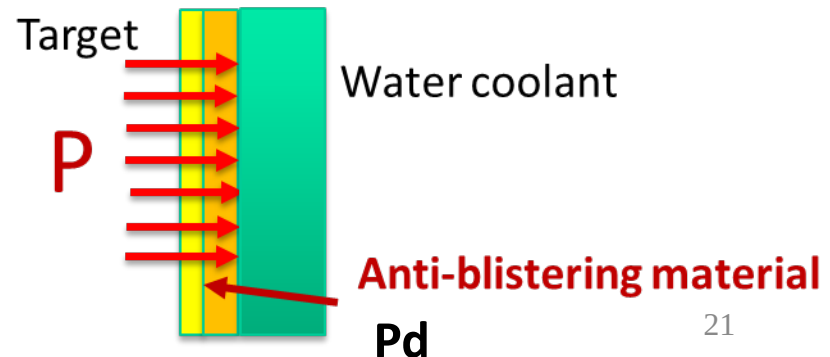
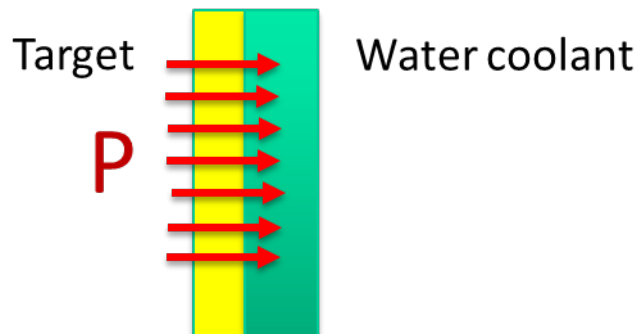
C-BENS monolith Be target in Japan
30 MeV proton



iBNCT layered target in Japan
8MeV proton



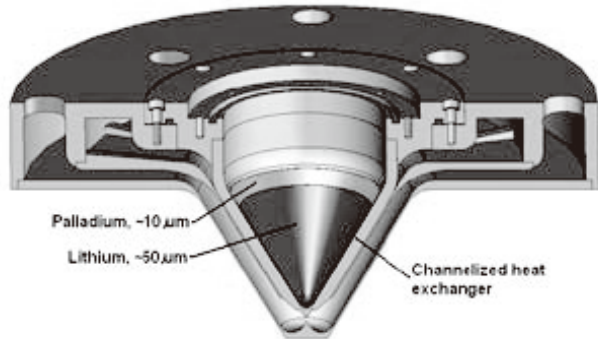
*H. Kumada, T. Kurihara, M. Yoshioka,
et al., Applied Radiations and Isotopes
106 (2015) 78-83.



Li-targets

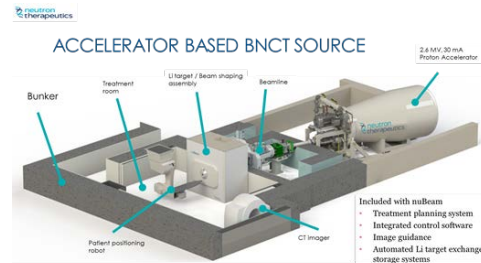
(Solid)

National Cancer Center in Japan



The Japanese journal of medical instrumentation, 84, 5 (2014).

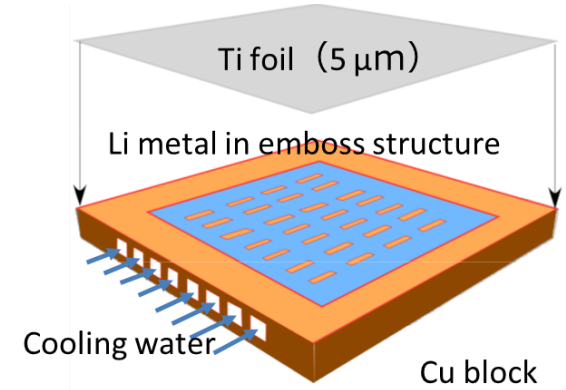
Neutron Therapeutic INC



Rotating target

<http://www.neutrontherapeutics.com/>

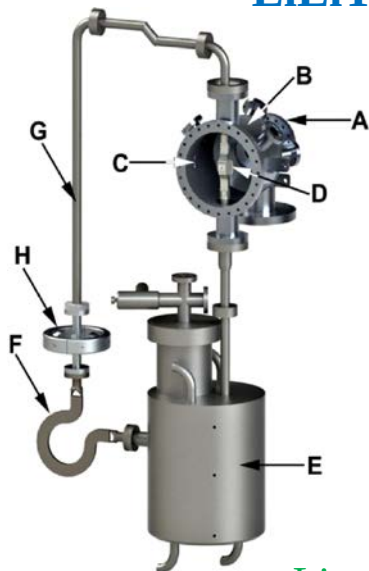
Nagoya University in Japan



Sealed target

(Liquid)

LiLiT-SARAF in Israel



App Radiat Isot
2015; 106:57-62.

Liq. Li loop at Osaka University in Japan



App Radiat Isot 2015; 106:92-94

Liq. Li systems have not been used at AB-BNCT hospital.

Epithermal moderator materials

Neutrons are moderated from about MeV to sub-eV. (Epithermal source)

***Classical collision and Inelastic scattering mainly contribute to the slowing down.**

1. Classical mechanics of slowing down

E_1 : Energy before the collision, E_2 : Energy after the collision

v_1 : Velocity before the collision, v_2 : Velocity after the collision,

$$\frac{E_2}{E_1} = \frac{v_2^2}{v_1^2} = \frac{A^2 + 2A \cos \theta + 1}{(A + 1)^2}$$
$$\alpha \equiv \left(\frac{A - 1}{A + 1} \right)^2 \quad \begin{array}{l} A = M_A / m_n \doteq \\ \text{Mass number} \end{array}$$

$$\frac{E_2}{E_1} = \frac{1}{2} [(1 + \alpha) + (1 - \alpha) \cos \theta]$$

θ : Scattering angle in the center of mass system (CMS)



Similar to billiard

Minimum energy getting to by one collision

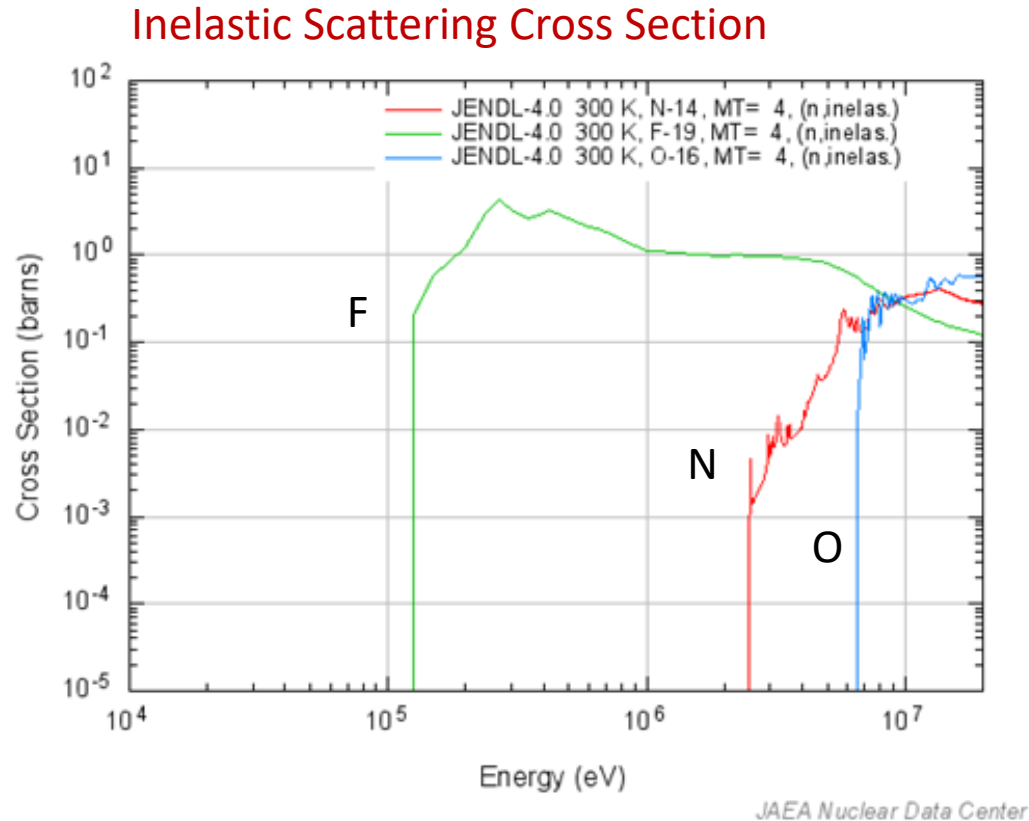
$$E_{\min} = \alpha E_1$$

Small $A \rightarrow$ small α : H, D, Be, C $\rightarrow$ effective thermal moderator $\rightarrow$ Water in a body
 $A \sim 20$ will fit to epithermal. $^{19}\text{F} \rightarrow$ good epithermal moderator

2. Inelastic scattering cross section

*Comparison of N, O and F inelastic cross sections.

F has much lower threshold energy than N and O in inelastic scattering.



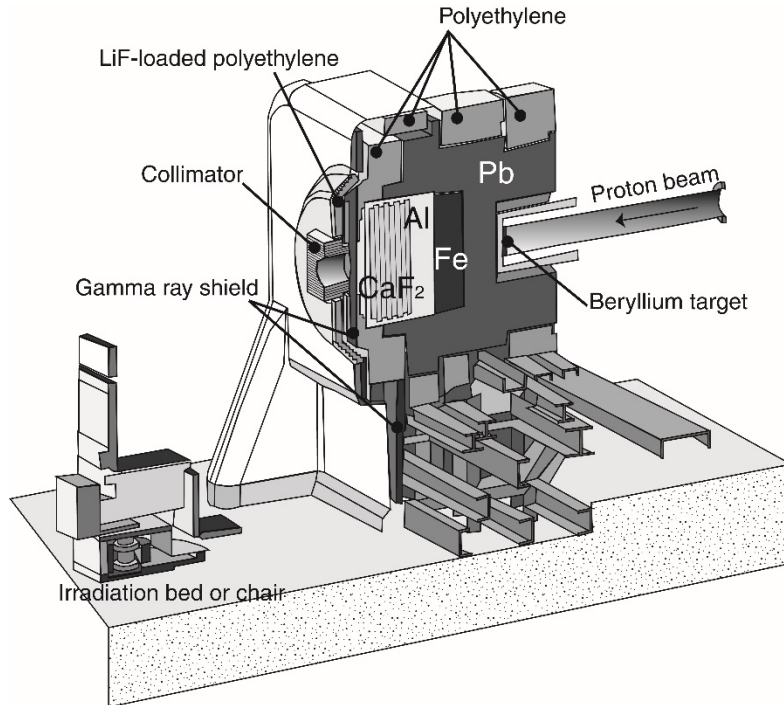
* MgF_2 , CaF_2 and AlF_3 are candidates.

*Composite material, Fludental, is also a candidate.

* $(\text{CF}_2)_n$ will have good neutronic characteristics but radiation damage will be serious than others.

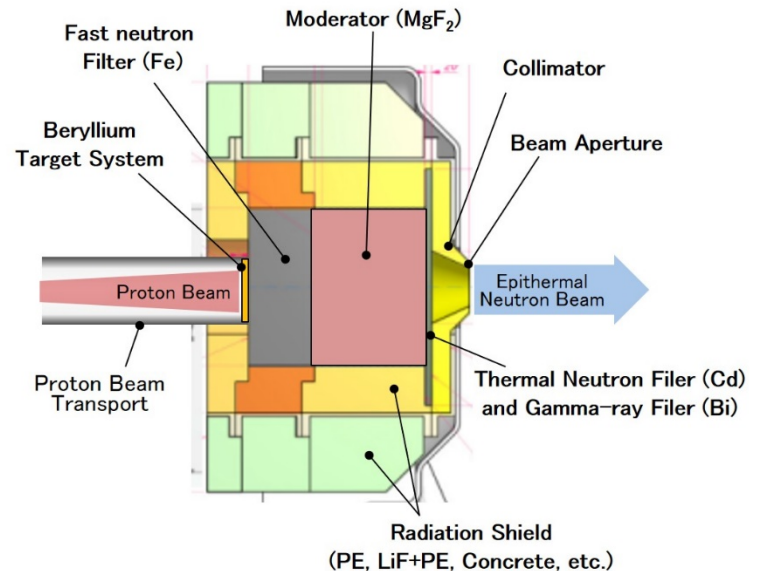
BSA Structure

C-BENS at Kyoto University in Japan
30MeV Cyclotron



IEEE Nuclear Science Symposium Conference Record
2009, Article number 5402230, Pages 2355-2357.

iBNCT in Japan
8MeV Linac

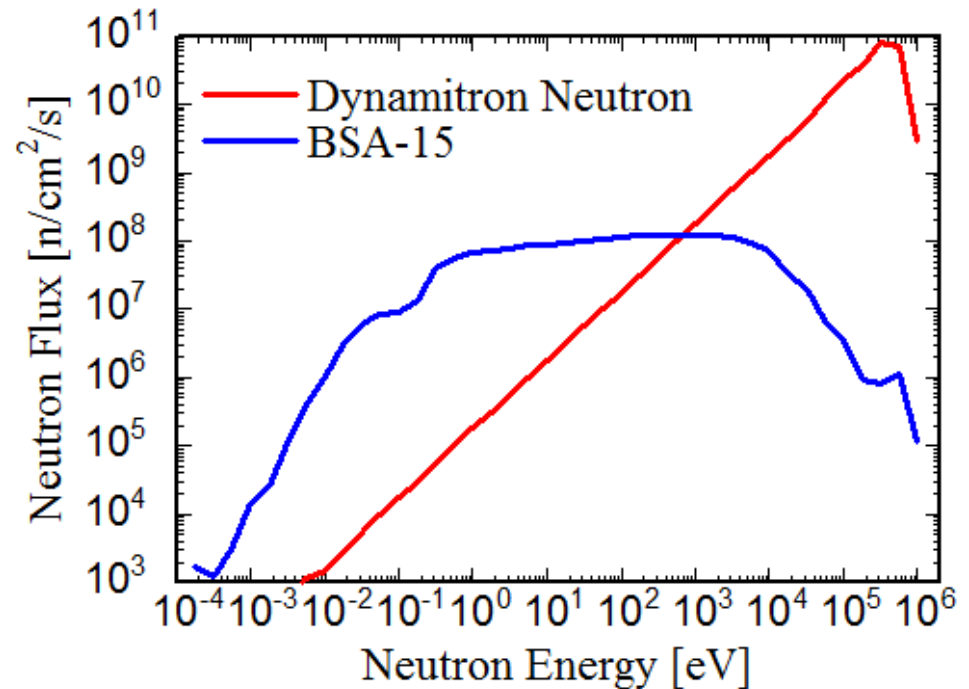
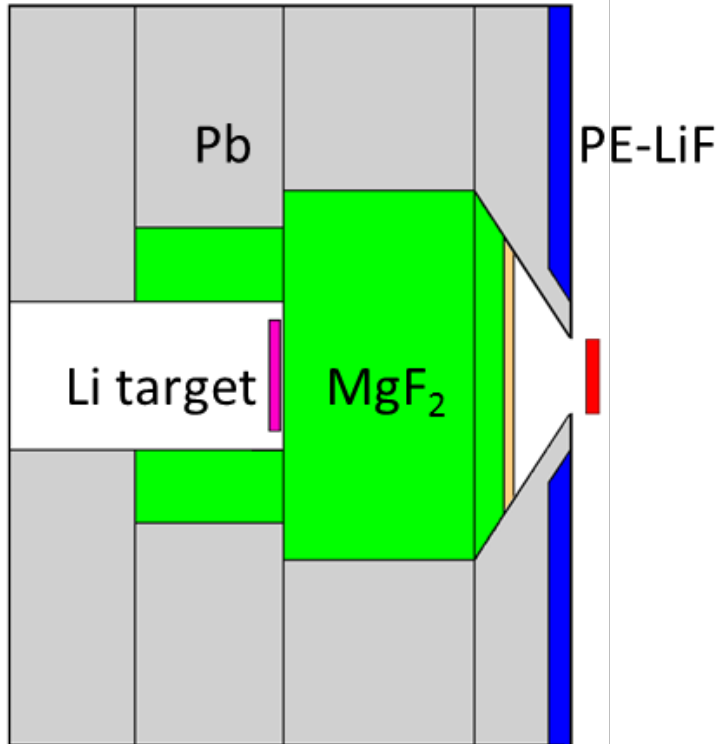


Plasma and Fusion Research: Regular
Articles 2018; 13: 2406006.

The world first AB-BNCT

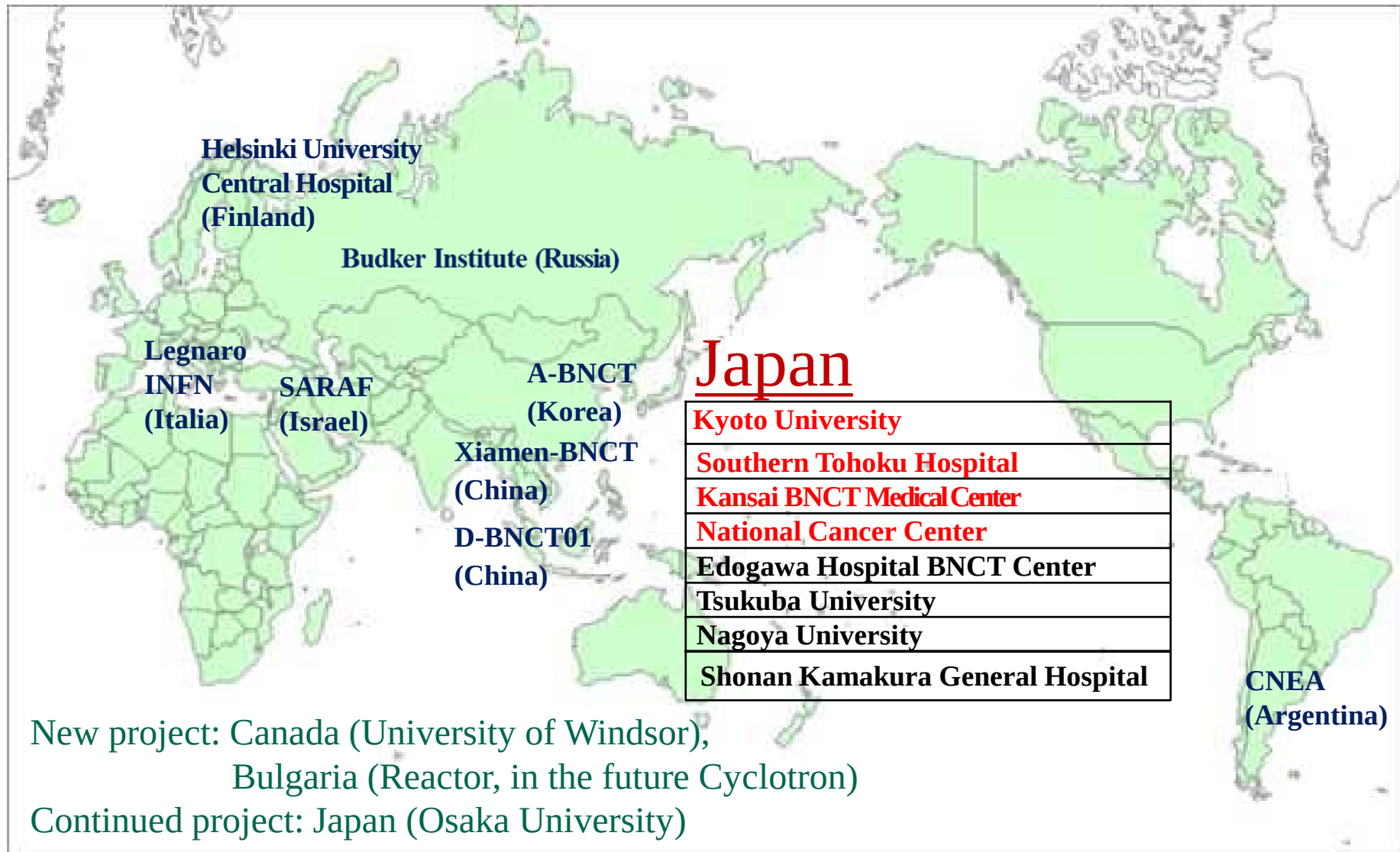
An example of the BSA performance

2.8 MeV electrostatic accelerator



Epithermal neutron flux	$N_{\text{epi}} [\times 10^9 \text{ n/cm}^2/\text{s}]$	1.89
Fast neutron component	$D_f [\times 10^{-13} \text{ Gy} \cdot \text{cm}^2]$	1.99
g-ray component	$D_g [\times 10^{-13} \text{ Gy} \cdot \text{cm}^2]$	1.69
Thermal neutron ratio	$N_{\text{t/e}}$	0.047
Current · Flux ratio	C/F	0.704

Accelerator based BNCT neutron sources in the world



BNCT facilities based on accelerators are under operation, construction and planned in various countries. **Red character facilities in Japan** have started clinical trial or treatment.

List of accelerator based BNCT facilities in the world

Facility name	Accelerator	Target	Incident particle, Produced neutron energy (MeV)	Designed current (mA)	Present status
1. Kyoto University, C-BENS	Cyclotron	Be	P: 30 , N: < 28	1	Clinical trial has ended.
2. Southern Tohoku Hospital	Cyclotron	Be	P: 30 , N: < 28	1	Treatment
3. Tsukuba University	Linac	Be	P: 8 , N: < 6	5	Physical meas.
4. National Cancer Center	Linac	Solid Li	P: 2.5 , N: < 1	20	Clinical trial
5. Kansai BNCT Medical Center	Cyclotron	Be	P: 30 , N: < 28	1	Commissioning
6. Edogawa Hospital BNCT Center	Linac	Solid Li	P: 2.5 , N: < 1	20	Commissioning
7. Shonan Kamakura General Hospital	Electrostatic	Solid Li	P: 2.6 , N: < 1	30	Construction
8. Nagoya University	Electrostatic	Solid Li	P: 2.8 , N: < 1	15	Commissioning
9. Budker Institute (Russia)	Electrostatic	Solid Li	P: 2.0-2.3 , N: < 1	10	Developing
10. Helsinki University Central Hospital (Finland)	Electrostatic	Solid Li	P: 2.6 , N: < 1	2.6	Commissioning Treatment (2021)
11. SARAF (Israel)	Linac	Liq-Li	P: 2.5 , N: < 1	20 (?)	Developing
12. CNEA (Argentina)	Electrostatic	Be, ¹³ C	P, d: 1.45 , N: < 6	30	Constructing
13. INFN (Italia)	Linac	Be	P: 5 , N: < 2	30	Developing
14. A-BNCT (Korea)	Linac	Be	P: 10 , N:<8	8	Commissioning
15. Xiamen BNCT Center (China)	Electrostatic	Solid Li	p: 2.5 , N:<1	10	Commissioning
16. D-BNCT01 (China)	RFQ linac	Solid Li	P: 3.5 , N<1.5	10	Commissioning

Revised from ref: Y. Kiyanagi, Y. Sakurai, H. Kumada, H. Tanaka, AIP Conf. Proc. 2160, 050012 (2019).

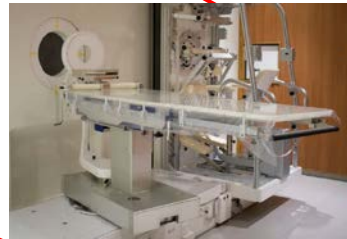
If there are mistakes, please let us know them.

Accelerator based BNCT facilities in Japan

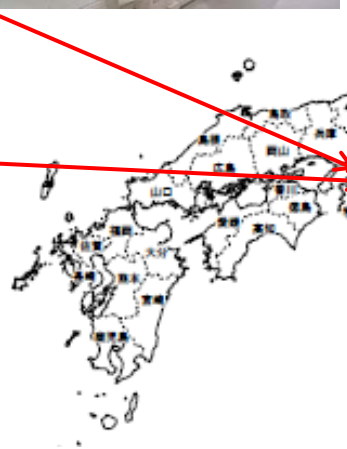
Southern Tohoku Hospital
(Treatment)
(Be target)
30MeV, 1mA



Osaka Medical college
(Kansai BNCT Medical Center)
(Treatment)
(Be target)
30MeV, 1mA



Kyoto Univ. C-BENS
(Clinical trial has ended.)
(Be target)
30MeV, 1mA



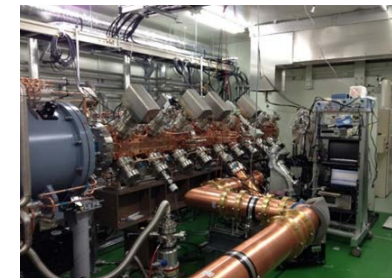
National Cancer Center
(Clinical trial)
(Solid Li target)
2.5MeV, 20mA



Edogawa hospital
(Construction)
(Solid Li target)

iBNCT
(Physical measurement)
(Be target)
8MeV, 5mA

Nagoya-U
(Commissioning)
(Solid Li target)
2.8MeV, 15mA



SHI's NeuCure is the first equipment that obtained approval from the Ministry of Health, Labour and Welfare in Japan in March 2020.

CONCLUSIONS/REMARKS

- The new TECDOC has to be thoroughly completed with the present situation concerning accelerator-based neutron sources and facilities.
- Topics should include: nuclear reactions being considered, accelerator types, targets and beam shaping assemblies (BSAs).
- The era of in-hospital neutron sources has started. Worldwide effort: a variety of different accelerators and nuclear reactions are being evaluated. So relative merits and costs may be compared.

