A Development Project of Boron Neutron Capture Therapy System based on a Linac Neutron Source

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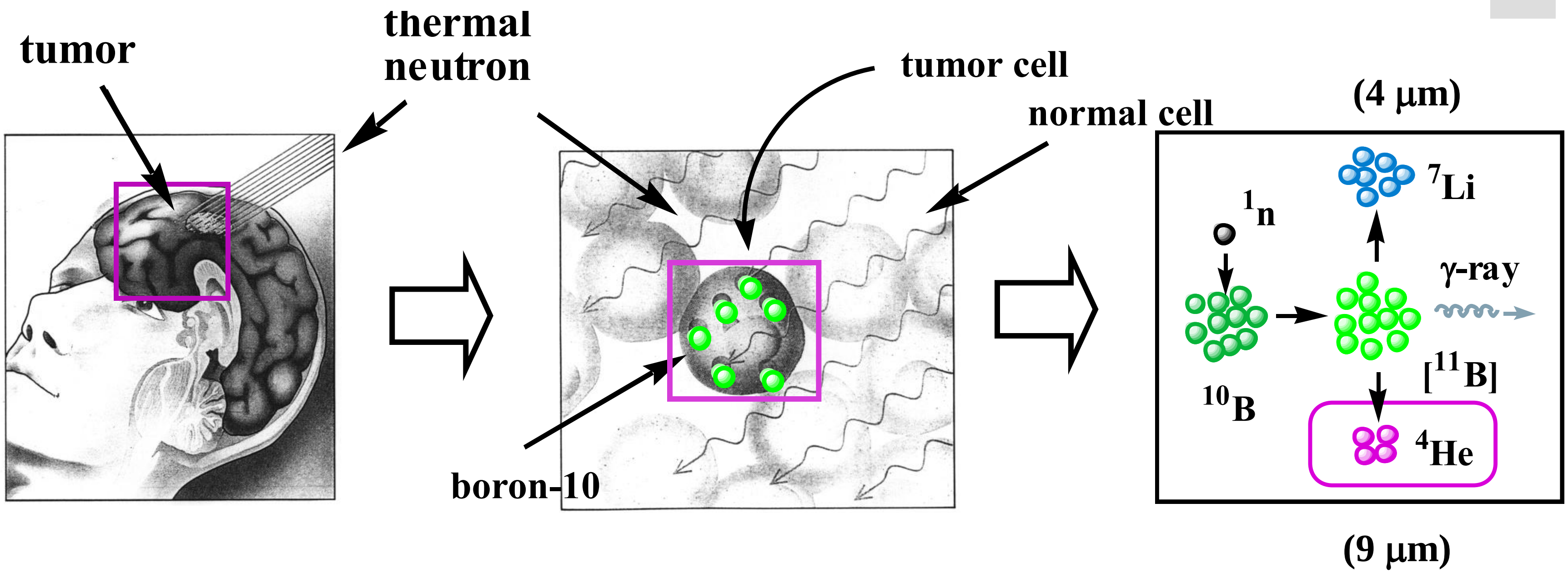
Principle of Boron Neutron Capture Therapy: BNCT

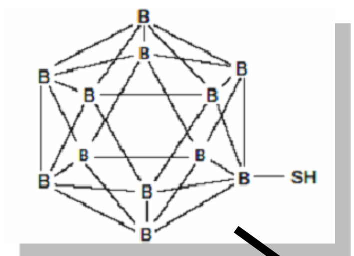


$$^{10}B + {}^{1}n \rightarrow [^{11}B] \rightarrow {}^{7}Li + {}^{4}He + 2.79\ MeV$$

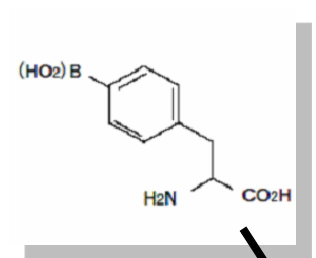
BNCT is a tumor cell selective charged particle therapy.

BNCT protocol for Glioblastoma

BSH 100mg/kg
1hr infusion



BPA250mg/kg
1hr infusion



Epithermal beam
30min

Positioning

0h 9.5h 11h

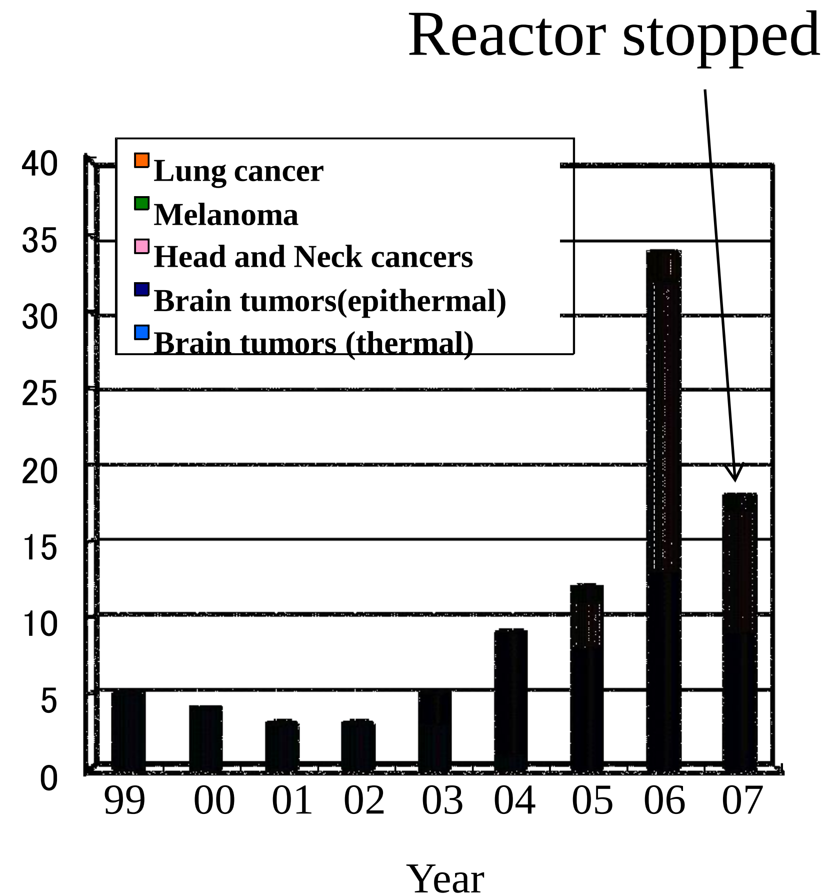
Surgery ^{18}F-BPA-PET BNCT

X –ray radiation 30Gy/15fr

6wks

University of Tsukuba

BNCT at JRR-4

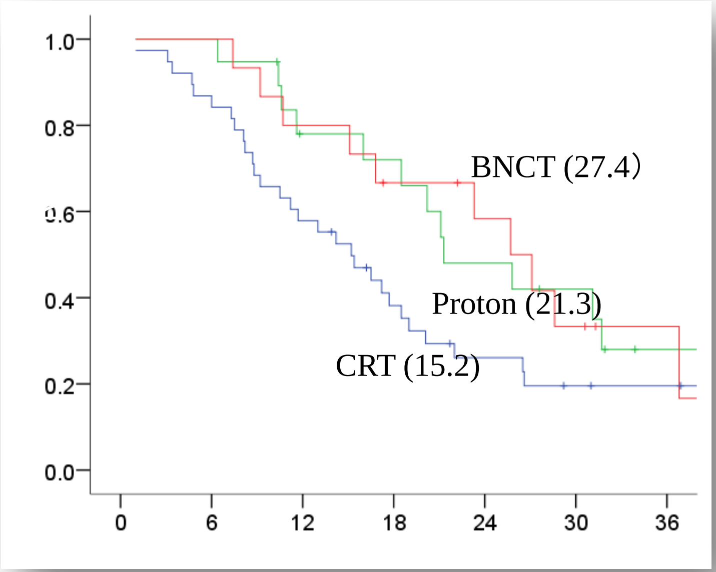


BNCT treatments are increasing.

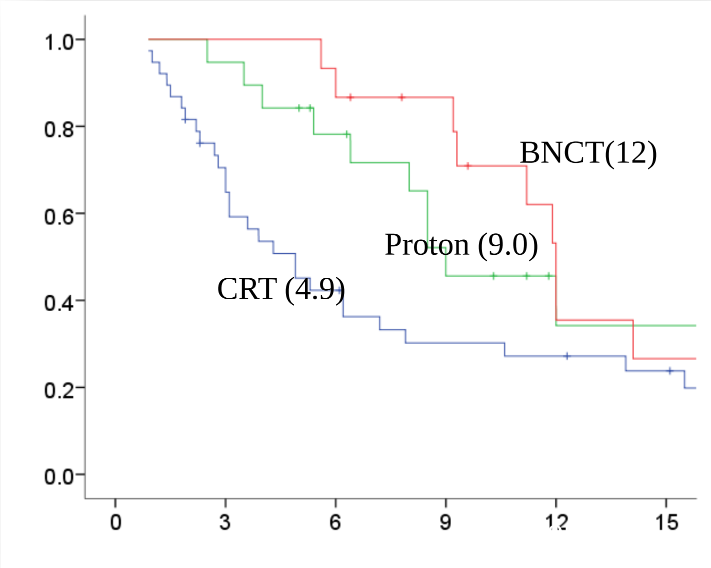
(provided by Dr. Kumada)

Survival rate ; newly-diagnosed Glioblastoma (n=71)
Comparison of CRT, proton & BNCT at TUV
（1998-2007）

Overall survival



Progression free survival



BNCT is superior to CRT and proton therapy both in progression free survival and overall survival

CRT: conventional radiation therapy

Choice of reactions (Preliminary optimization of a moderator)

- Li(p,n) reaction

Method ①: Direct use of neutrons produced by 1.9MeV proton

➡ The energy of the produced neutrons is low enough to use the neutron for BNCT

Method ②: Use of the moderated neutrons produced by 2.5-3.0MeV protons

➡ The energy of the produced neutrons is little bit higher but the intensity is also higher. The required moderation will be not so severe, so reduction is not so much.

- Be(p,n) reaction

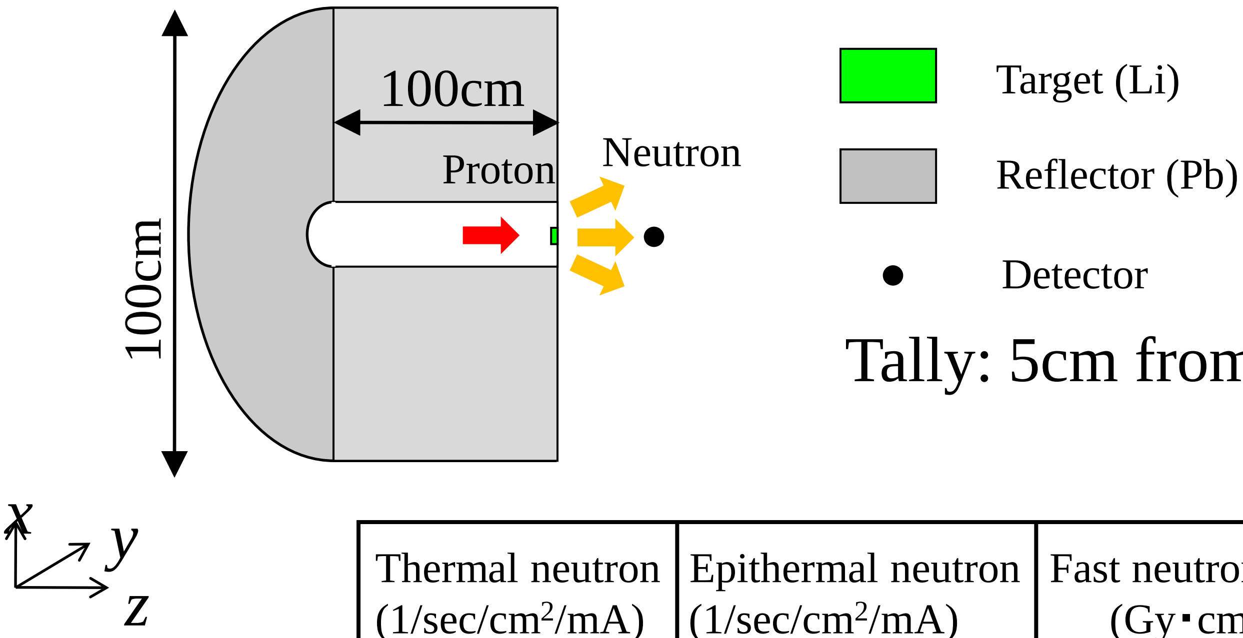
Method ③: Use of the moderated neutrons produced by 11MeV protons

➡ The neutron energy is much higher than Li(p,n) reaction, but the intensity is about 15 times higher. So, we will get enough intensity even after moderation.

	Ep	Neutron intensity	Neutron energy	
Li(p,n)	1.9MeV	1.5×10^{10} (n/sec/mA)	Max. 90 keV	Ave. 38keV
	2.5MeV	8.8×10^{11} (n/sec/mA)	Max. 787keV	Ave. 326keV
Be(p,n)	11MeV	2.15×10^{13} (n/sec/mA)	Max. 8.55MeV	Ave. 2.37MeV

①Direct use of Li(p,n) neutrons

- Simulation code：MCNPX



Tally: 5cm from a target

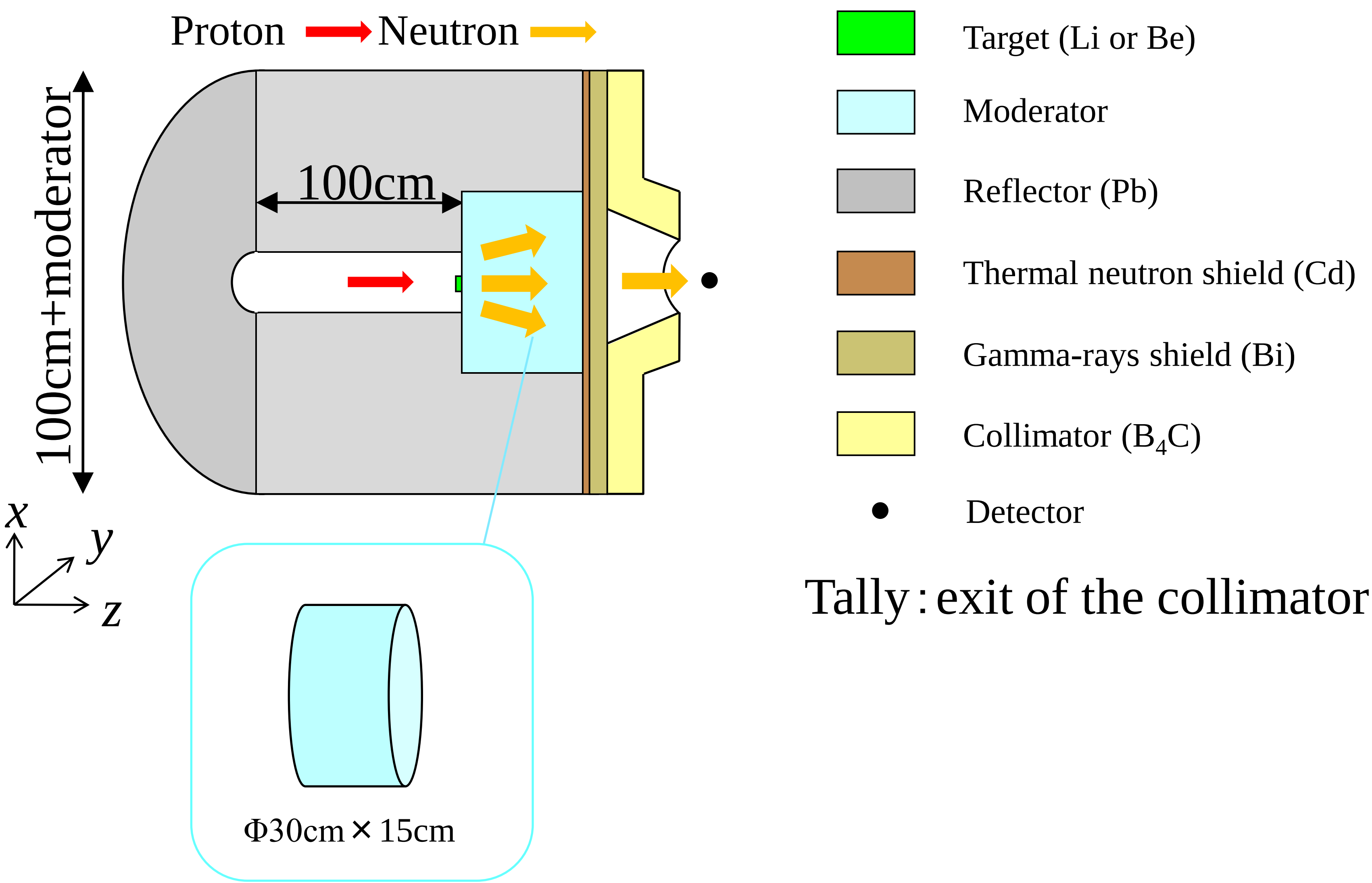
Thermal neutron (1/sec/cm²/mA)	Epithermal neutron (1/sec/cm²/mA)	Fast neutron dose/ϕ_{epi} (Gy・cm²)
2.11×10^3	1.29×10^8	3.63×10^{-12}

Fast neutron dose/ϕ_{epi} should be less than 1.0×10^{-12} (Gy・cm²)

➡ This method cannot fulfill the condition of Fast neutron dose/ϕ_{epi} that must be less than 1.0×10^{-12} (Gy・cm²).

②Li(p,n) reaction, ③Be(p,n) reaction —Slab type—

- Simulation code：MCNPX



Tally：exit of the collimator

Moderated neutron case —Slab type—

Ep (MeV)	Moderator size	Thermal n (1/sec/cm^2/mA)	Epi-thermal n (1/sec/cm^2/mA)	Fast n dose/ϕ_{epi} (Gy・cm^2)
2.5	Φ36cm×21cm	3.29×10^{3}	2.79×10^{7}	1.00×10^{-12}
2.6	Φ38cm×22cm	4.81×10^{3}	3.09×10^{7}	1.00×10^{-12}
2.7	Φ30cm×24cm	3.75×10^{3}	3.16×10^{7}	9.96×10^{-13}
2.8	Φ36cm×25cm	6.36×10^{3}	3.17×10^{7}	9.84×10^{-13}
2.9	Φ40cm×26cm	9.11×10^{3}	3.19×10^{7}	9.96×10^{-13}
3.0	Φ40cm×27cm	9.25×10^{3}	3.23×10^{7}	1.00×10^{-12}
11	Φ50cm×40cm	9.10×10^{5}	1.63×10^{8}	1.00×10^{-12}

①Thermal n<5.0×10^{7} (1/sec/cm^2)
②Epi-thermal n> 1.0×10^{9} (1/sec/cm^2)
③Fast n dose/ϕ_{epi}<1.0×10^{-12} (Gy・cm^2)
(Thermal n< 0.5eV Epi-thermal 0.5eV～10keV Fast n >10keV)

Minimum current of the accelerators
Li(p,n): 30.96mA (Ep=3.0MeV), Be(p,n): 6.13mA (11MeV)

Overall Plan of the Development Project

1. Accelerator for BNCT

Compact proton Linac which can install in a hostital (<100m^2)

Proton Beam Spec. : around 10MeV x a few mA beam on average

2. Neutron Source System

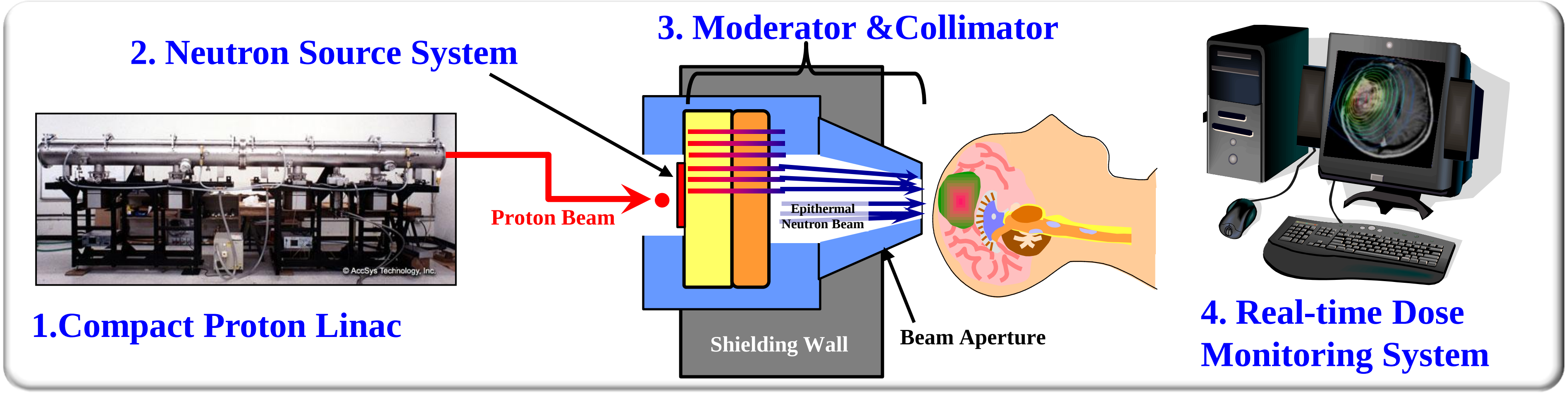
High Flux Neutron Generator & Cooling System

Neutron Target Material : Be, C, etc.

3. Moderator and Collimator

Optimum Design of Neutron Moderator and Collimator

Goal : Epithermal neutron: >1x10^9 (n/cm^2/s) at beam aperture



Accelerator design concept for BNCT

- Technology choice:
  - Cyclotron or Linac?
  - Parameters
    - Beam energy
    - Beam power (duty and peak beam current)
- The highest-priority issue:
  - Target system as a medical facility
    - Cooling method for high-density heat load
    - Maintenance for highly-activated target system
- Technology choice should be based on the above issues.

Accelerator design concept for BNCT

- **Technology choice:**
  - **Cyclotron or Linac?➔Linac: IS+RFQ+DTL(or IH)**
  - **Parameters**
    - **Beam energy ➔8MeV**
    - **Beam power (duty and peak beam current) ➔>40kW**
- **The highest-priority issue:**
  - **Target system as a medical facility**
    - **Cooling method for high-density heat load**
    - **Maintenance for highly-activated target system**
- **Technology choice should be based on the above issues.**

Requirement for BNCT accelerator #1

ITEM	JRR-4	PERFORMANCE GOAL	MINIMUM GOAL	CYCLOTRON (KYOTO UNIV.)
Beam spectrum	Epi-thermal neutron beam (1 eV ~ 10 eV)			
Fluence during treatment (n/cm^2)	~ 4.0 x 10^{12} (BNCT protocol for a brain tumor)			
Expose time per treatment (min.)	~17	<30	<60	~37
Maximum generated thermal neutron flux in a living body (n/cm^2/s)	4.0 x 10^9	>2.2 x 10^9	>1.1 x 10^9	1.8 x 10^9
Maximum generated γ-Ray flux in a living body (Gr/h)	~6	≤4.2	≤2.1	~3.5
Free beam epi-thermal neutron flux (n/cm^2/s)	2.2 x 10^9	>1.2 x 10^9	>0.6 x 10^9	~1.0 x 10^9
γ-Ray flux in free beam (Gr/h)	~1.2	<1.2	<0.6	~10?
γ-Ray contamination (Gr·cm^2/n)	1.5 x 10^{-13}	≤3.0 x 10-^{13} (IAEA: 2 x 10^{-12})	≤3.0 x 10^{-13}	3.0 x 10^{-13}?
Fast neutron contamination (Gr·cm^2/n)	3.1 x 10^{-13}	≤1 x 10^{-12} (IAEA: 1 x 10^{-12})	≤1 x 10^{-12}	~1 x 10^{-12}
Proton beam energy (MeV)	-	LINAC: 8 MeV	LINAC: 10 MeV	30 MeV
Peak beam current (mA)	-	> 5 mA	> 3 mA?	1 mA
Output power (kW)	(3500 kW)	> 40 kW	> 30 kW?	30 kW
Target material	-	Be, Li etc.	Be, Li etc.	Be
Target life time (year or number of patient)	-	>half year or >100	>half year or >50	one year or 500~100?
Capacity of the facility (number of patient per year)	34 (@2007) available for >50 people	> 300	~40	> 100?

Requirement for BNCT accelerator #2
Issues as a medical facility

- ❑RAMS (Reliability, Availability, Maintainability and Safety)
- ❑Target system: long life time and easy maintenance
    - ❑life time > several months
    - ❑easy replacement
- ❑Small number of specialist can operate the whole system
    - ❑accelerator, target system, radiation safety, etc.
- ❑Small amount of radio-active waste
    - ❑Be target, tritium, shielding material (lead, steel, etc.)
- ❑Compact facility area < $100m^2$

These requirements are different from the accelerators for industry use.

Baseline accelerator technology
→ the front end of J-PARC linac

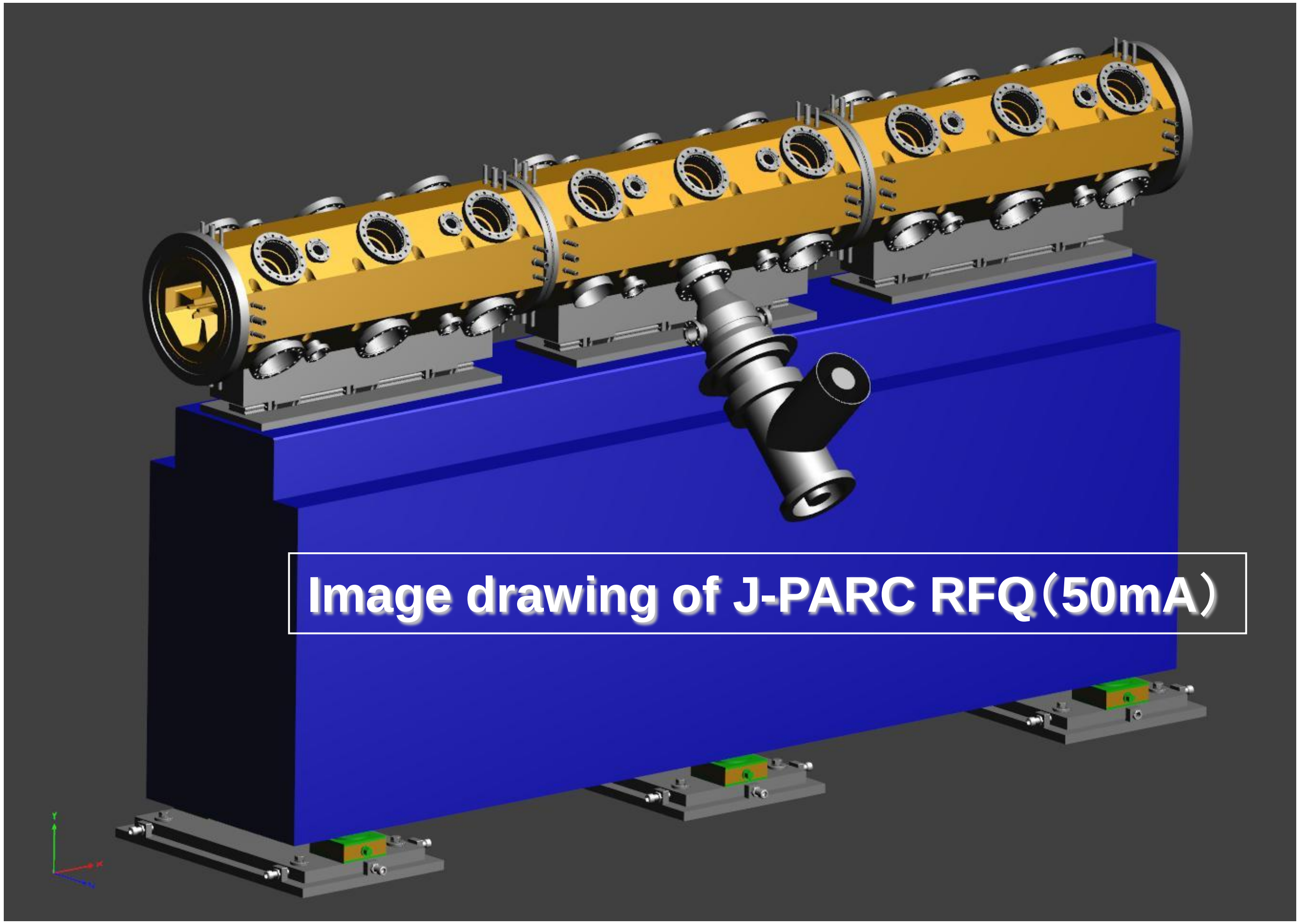
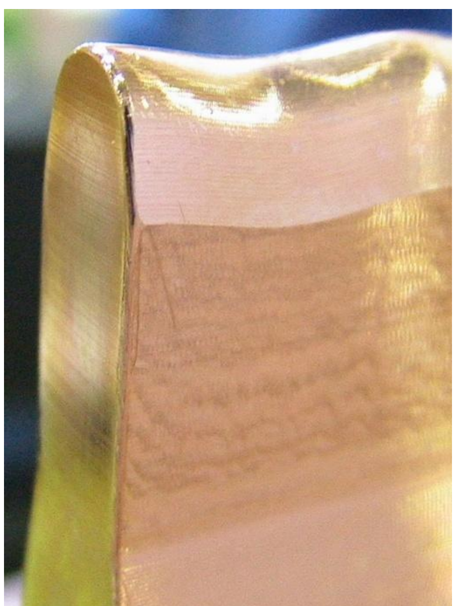
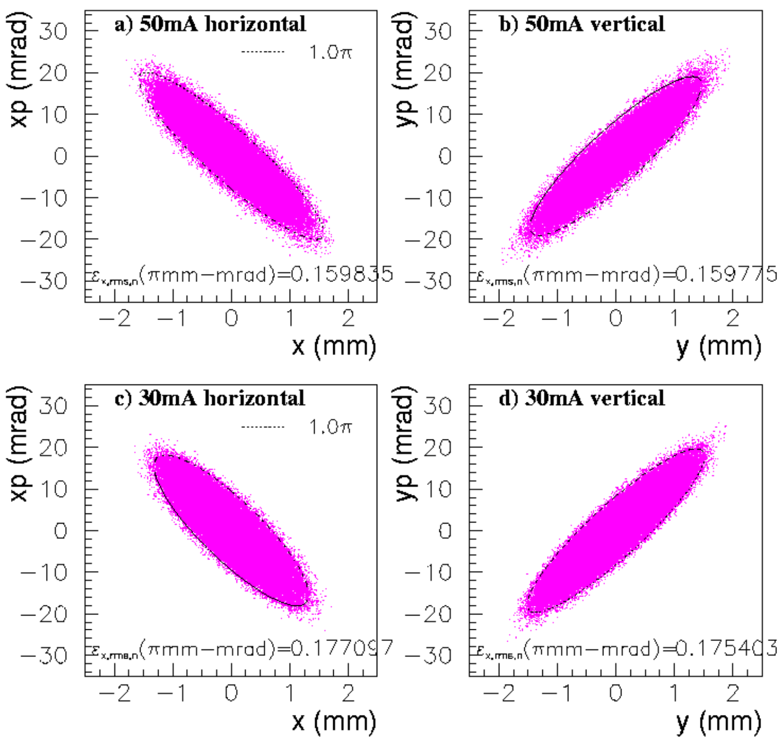


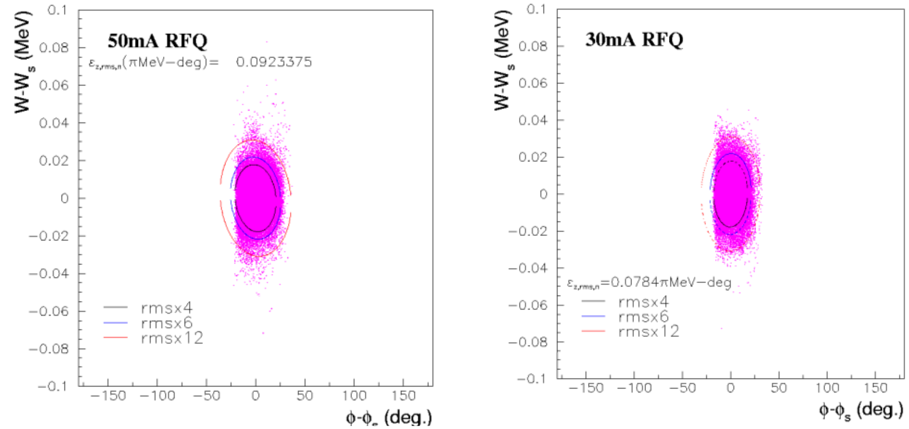
Image drawing of J-PARC RFQ（50mA）

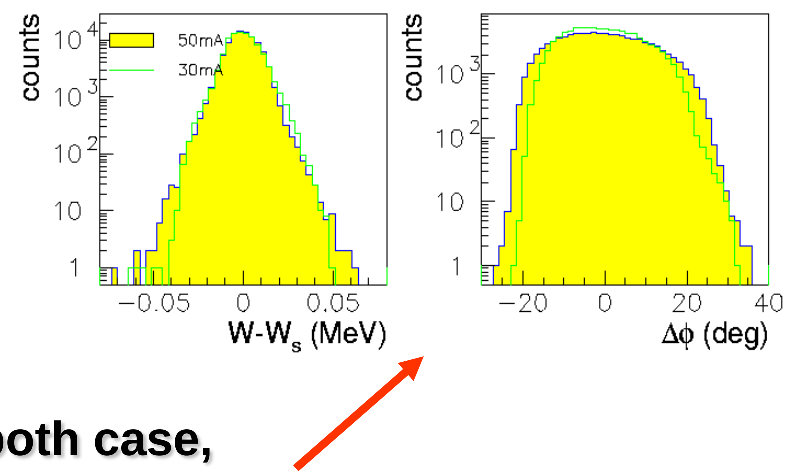
Photos in works



Phase space plot of the reference design of 30mA and 50 mA RFQ for J-PARC Courtesy of Y. Kondo

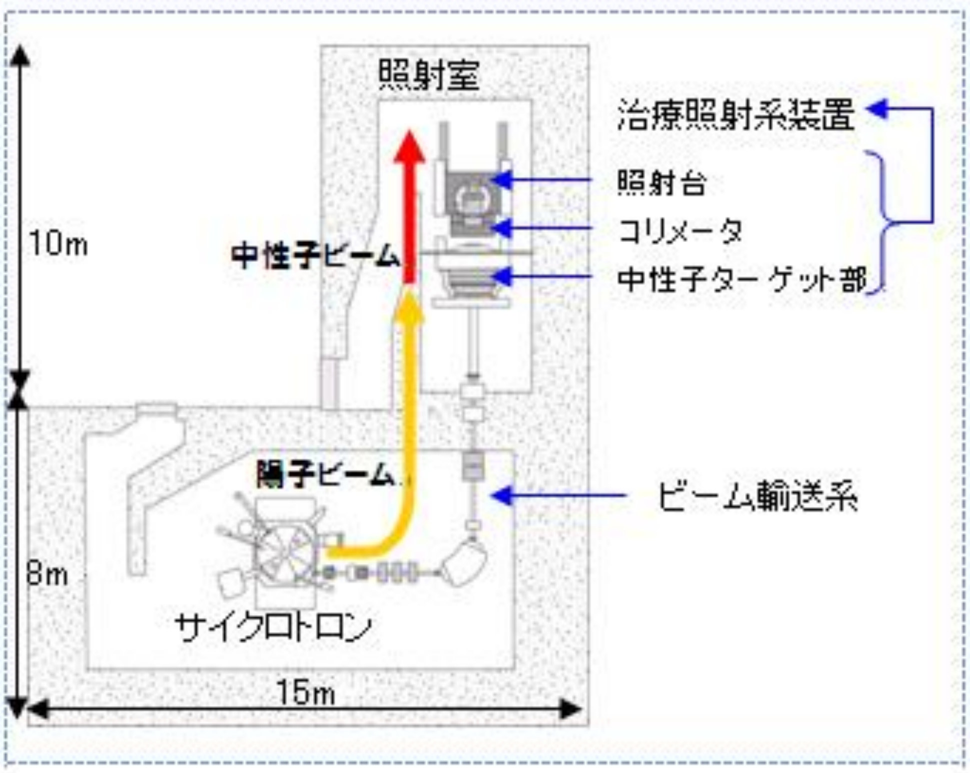






Transverse is almost same for both case, but longitudinal for 50mA is larger than the 30mA's one.

Kyoto University press release on August 5, 2009 → 30MeV, 1mA



Our technology choice is different, avoiding doubling!

Feasibility Study on a Common Use Accelerator System of Neutron Production for BNCT and Radionuclide Production for PET

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Table 4. Example specifications of a BNCT-PET common use accelerator.

Accelerated Particle	proton
Beam Energy (MeV)	11
Pulse Beam Current (mA)	30
Pulse Duration (μ sec)	200
Pulse Repetition Rate (Hz)	500
Average Beam Current (mA)	3.0

Target design by Hitachi

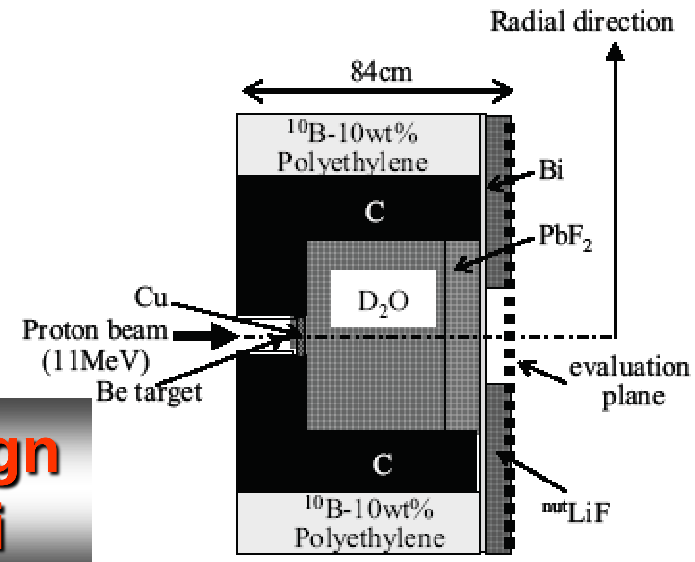


Fig.1. Cross-sectional view a moderator geometry for thermal neutron irradiation fields.

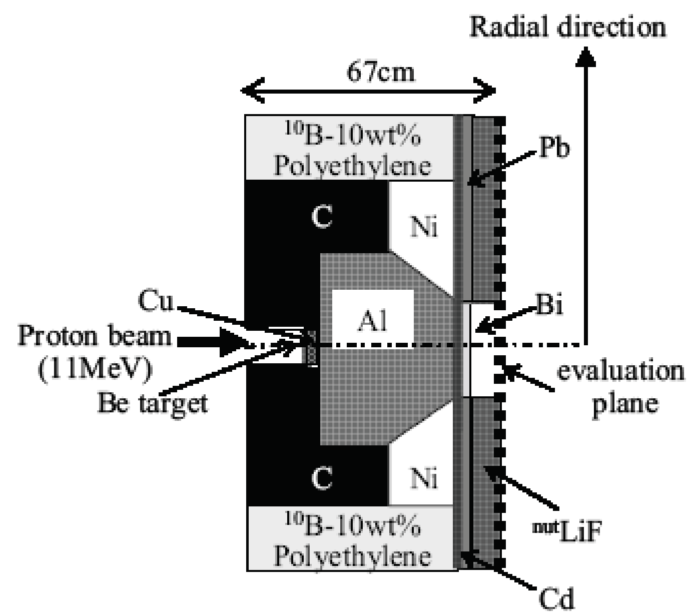


Fig.2. Cross-sectional view of a moderator geometry for epi-thermal neutron irradiation fields.

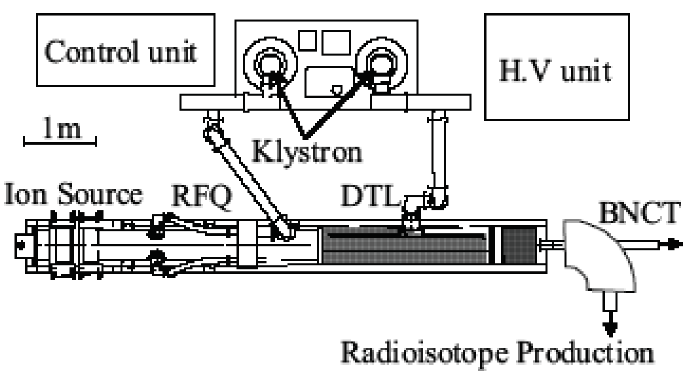
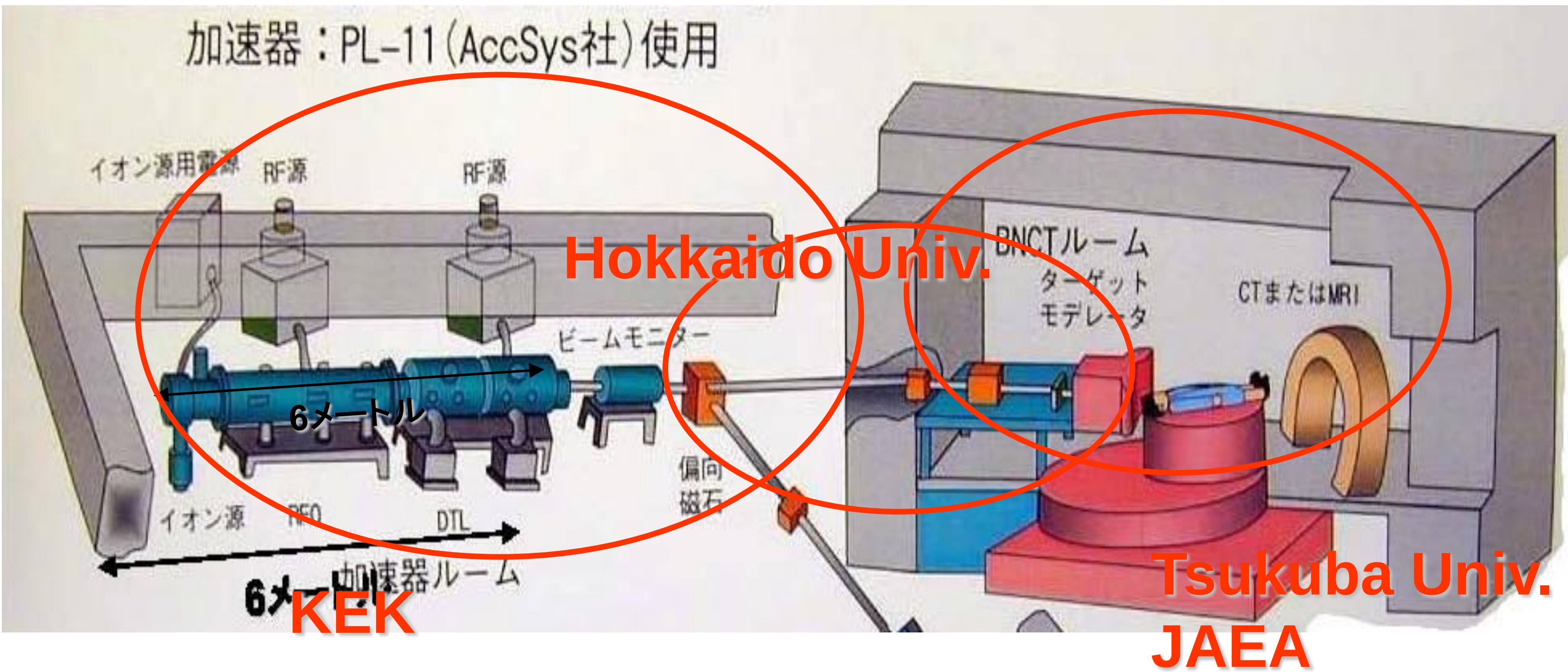


Fig.6. A schematic view of a BNCT-PET common use accelerator.

Conceptual drawing of BNCT accelerator system

Based on the HITACHI plan



Summary

We are just at beginning stage of the project for constructing the BNCT facility based on a proton accelerator.

There are many things to be developed and optimized concerning to the accelerator, the moderator system including a target, the collimator system, the shield, the activity and so on.

For such development and optimization UCANS collaboration is useful.

Thank you for your attention!