

Development of the Heat Sink Structure for a Beam Dump for a proton accelerator

2007. 6. 4

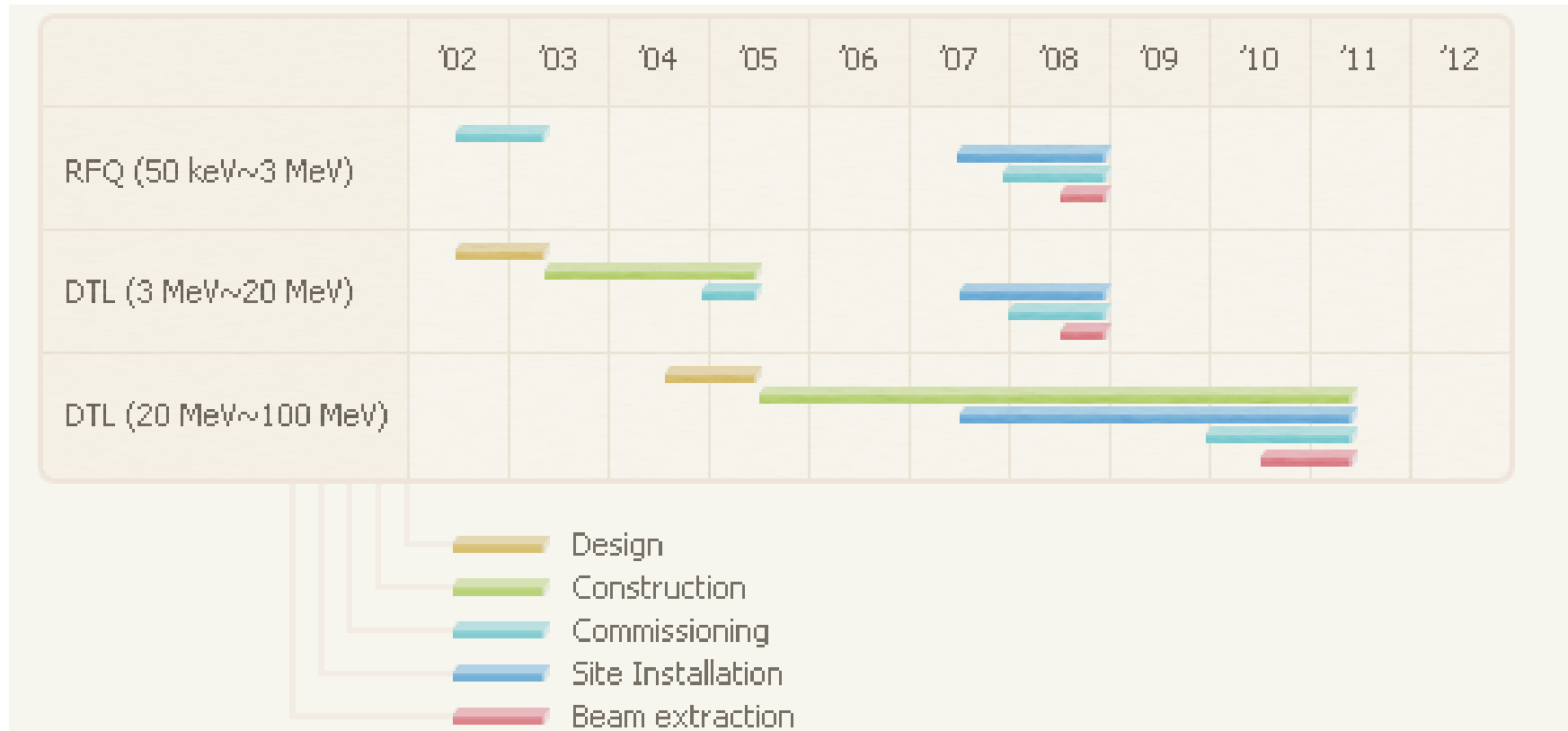
W. Y. Maeng



Korea Atomic Energy Research Institute

Schedule of Development of Proton Accelerator

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The final goal is to construct a proton linear accelerator which can accelerate proton beams of 20mA up to 100MeV

- Introduction
 - Beam Dump
- Design
 - Heat sink structure
 - Radio activity assessments
 - Cooling design
- Fabrication
 - Brazing
- Verification
 - Thermal fatigue
- Summary

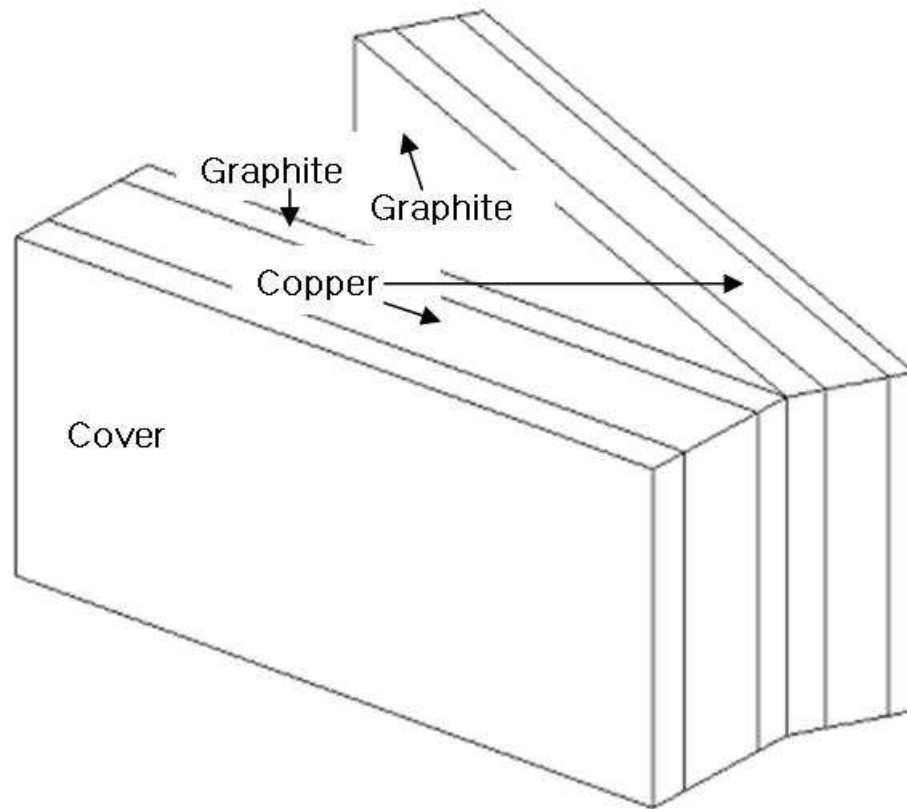


Overview of proton accelerator

- **A beam dump** is an essential component for a final treatment of the beam produced in a proton accelerator. **Reliable performance of a beam dump depends on the functions of a heat sink structure in the beam dump.**
 - The energy of 20 MeV, 20 mA proton beam produces very large amount of heats (96kW, duty factor: 24%) when the beam collides with heat sink structure of beam dump. Average heat flux of the beam of 1 cm diameter is about 1.223×10^3 MW/m². The power density of the proton beam in graphite is about 532kW/cm³. Comparing this value with the power density of PWR fuel of 0.21kW/cm³, **the power density of the proton beam is extremely high.**
 - **It is necessary to design the heat sink structure to have enough cooling capacity and to withstand the thermal stresses induced by the heats.** It is also required that the materials of the structure have **little radio-activation characteristics.**
 - The heat sink structure was made by placing two heat sink plates at an angle so that the maximum heat flux on the surface of the plate is as low as possible (12°). The heat sink plates were fabricated by a brazing of a graphite and copper plate.
 - The heat sink structure of the beam dump that satisfies the requirements was designed, fabricated and verified in this study

2. Design - heat sink structure of beam dump

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-The heat sink structure is composed with **two heat sink plates** as shown in the Figure.

- A heat sink plate is **composed of the graphite and the Cu plate.**

-The graphite and the Cu plate were **joined by brazing.**

2.1 Design - heat sink structure of beam dump

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Fig. 2 The maximum heat flux on the surface of graphite plate as a function of plate angle.

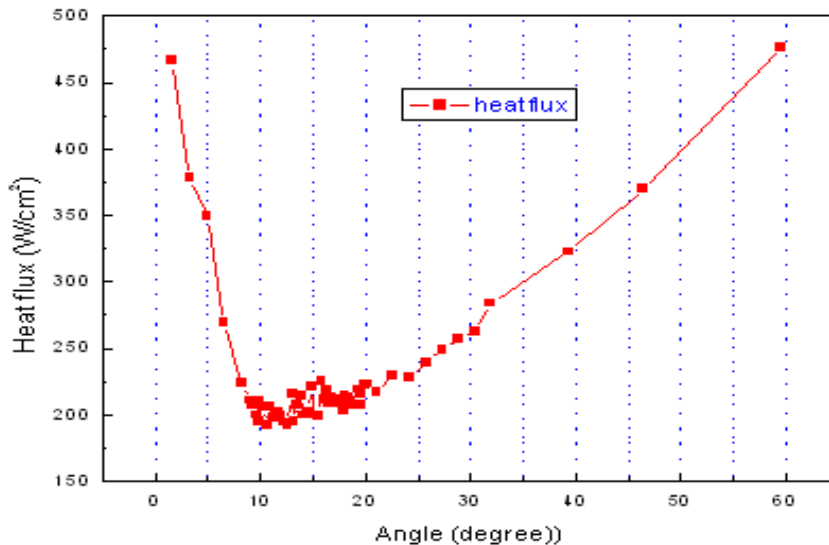
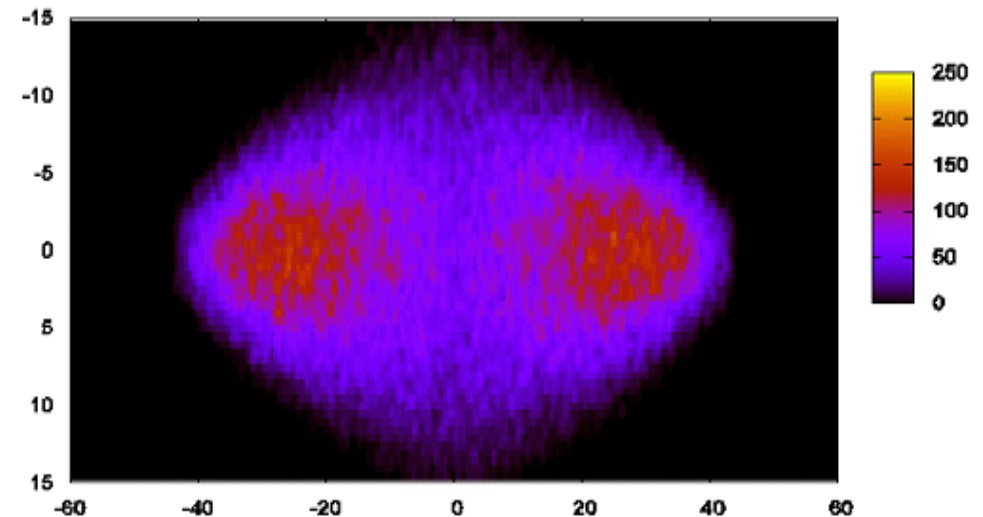


Fig.3 The heat flux distribution on a surface of graphite plate of the heat sink structure of plate angle of 11.5°



- The angle between the two plates was determined so as that the maximum heat flux on the surface of graphite plate is lowest in the range of angle between 0° ~ 60°.
- The maximum heat fluxes on the surface of graphite plate as a function of plate angle were calculated and shown in Fig. 2. (an angle of 12° :the lowest maximum heat flux).
- The heat flux distribution on a surface of graphite plate of the heat sink structure of plate angle of 11.5° is shown in Fig. 3.

2.2. The assessments of radioactivity

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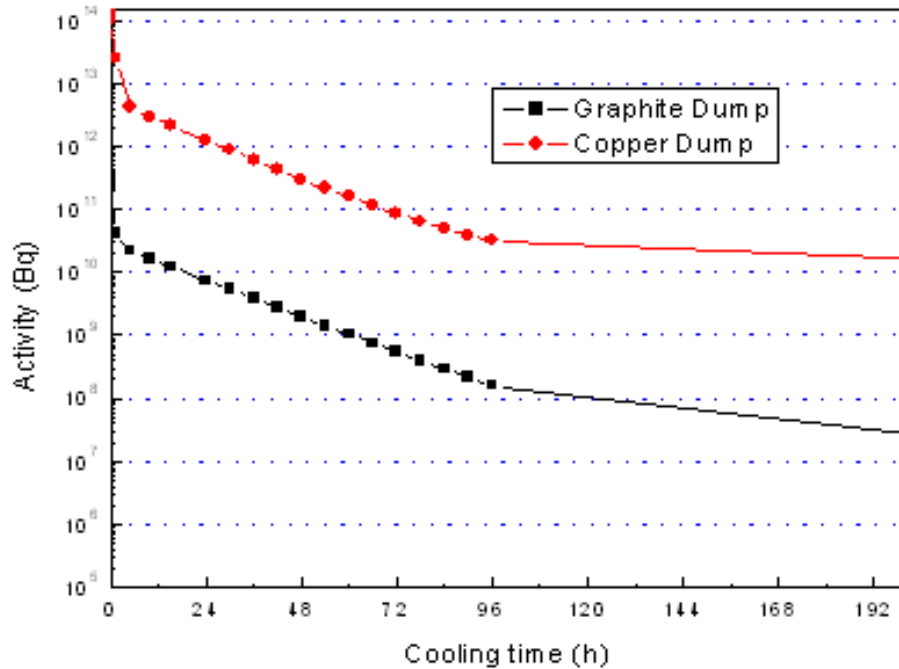


Fig. 4 Residual radioactivity after the proton beam (20MeV, 4.8mA) irradiation on the graphite-Cu heat sink structure for 3 hours

- The assessments of radioactivity of the composed materials are essential procedure for the design of the heat sink structure of a proton beam dump because the residual radioactivity influences the operation mode of the proton accelerator itself as well as the safety of operator.
- The graphite was chosen as the front face of the heat sink plate because the materials have the advantages of the activity reduction and the high stopping power.
- The amount of the residual radioactivity of the Graphite and the Cu after the proton beam (20MeV, 4.8mA) irradiation on the graphite-Cu heat sink structure for 3 hours is shown in Fig. 4. The residual radioactivity in the Cu is 400 times higher than that in graphite.

2.3. The cooling design

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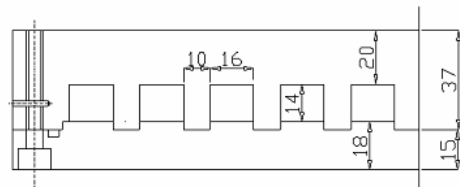
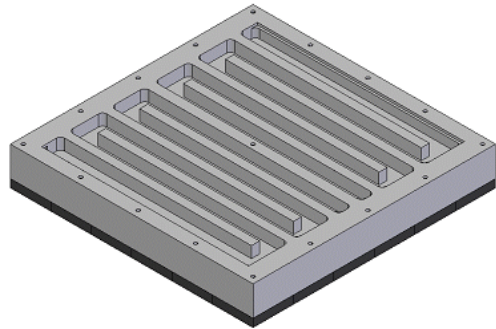


Fig. 5 Shape of cooling jacket

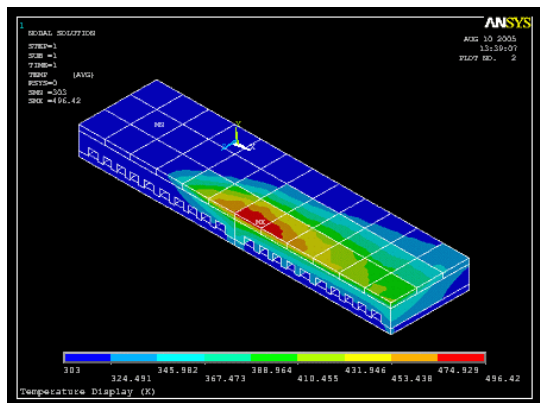


Fig. 6 Temperature distribution of the cooling jacket

- The schematic shape of the Cu cooling jacket (30cm x 30 cm) that is joined with graphite front face is shown in Fig. 5. The Cu cooling jacket has two parts (1) part facing graphite, 2) part facing water).

- Average heat flux (q'') from the water contacting surface of the cooling jacket (of the part facing graphite) to the cooling water is calculated as this equation.

$$q'' = 2(\text{safety factor}) \times 24 \text{ kW} / (30 \times 30) \text{ cm}^2 = 53.33 \text{ W/cm}^2$$

- The maximum heat transfer coefficient can be estimated if we suppose that the ΔT (Temperature difference between Cu surface and water) is 30° ;

$$H = q'' / \Delta T(30^\circ) = 17,778 \text{ W/m}^2\text{K}$$

- The heat transfer coefficient is calculated as 20,666 $\text{W/m}^2\text{K}$. So it is considered that the designed cooling system has enough cooling capacity.

- The results of heat transfer analysis are shown in Fig. 6. The highest temperatures of the graphite, copper, and copper faced by cooling water were evaluated to be 223°C , 146°C , and 85°C , respectively when the velocity of cooling water was 3 m/sec.

2.4. The stress analysis

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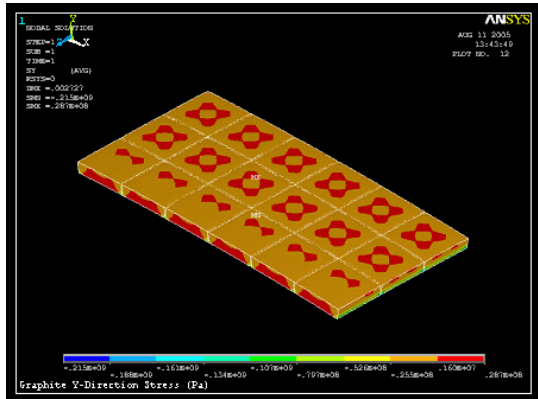


Fig. 7 Stress distribution of graphite in y direction after brazing

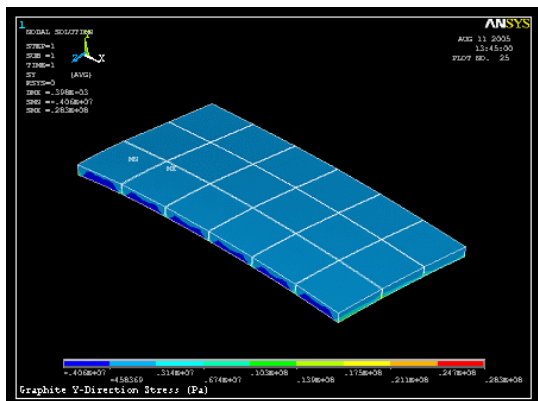


Fig. 8 Stress distribution of graphite in y direction during operation condition

-Stress analysis of the heat sink structure was carried out for the two case of stress situation: 1) the stress analysis after brazing, 2) the stress analysis during operation.

-The results of the stress analysis are shown in Fig. 7 and Fig. 8.

-The stress in the y direction is about **75%** of tensile strength as shown in Fig. 7 (**stress distribution after brazing**).

-**The operation stress analysis** also shows similar results in Fig. 8. The tensile stress of the graphite was less than **75%** of a maximum tensile stress during the accelerator operation based on the analysis.

3.1 Fabrication of heat sink structure: materials

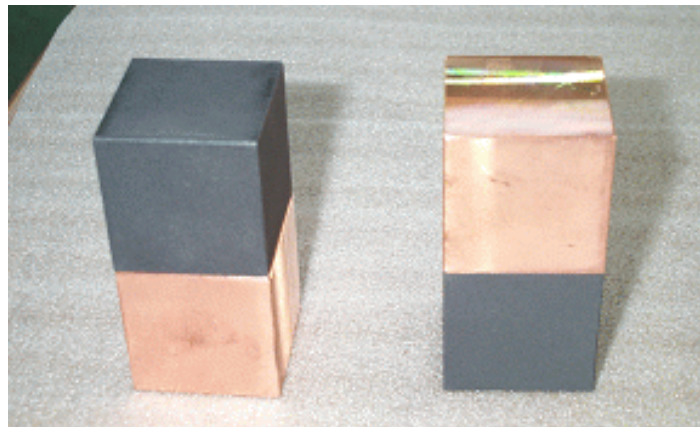
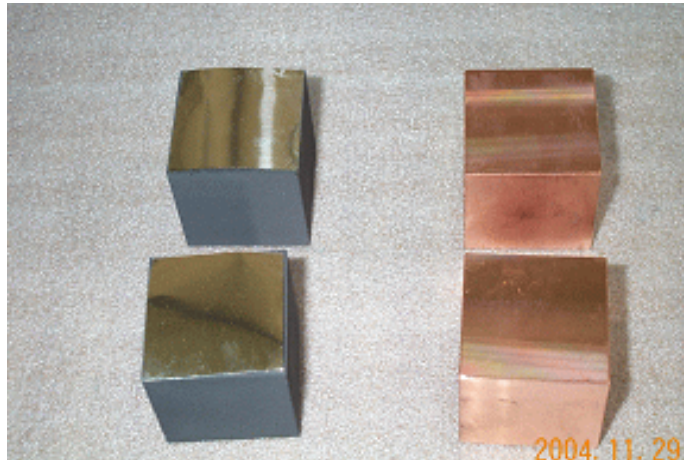
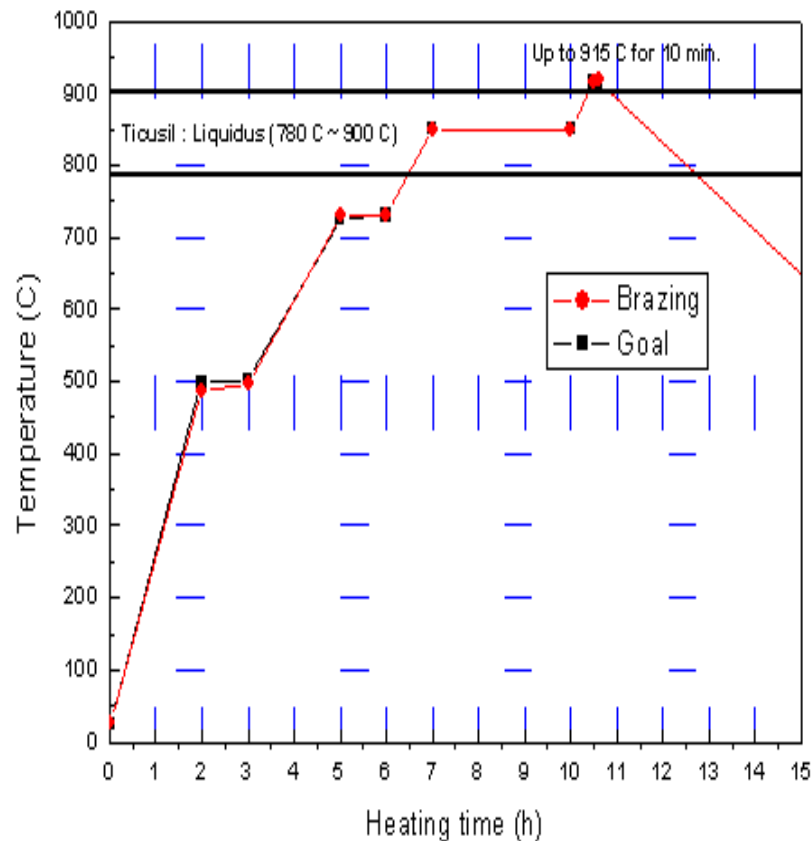


Fig. 9 The base materials and the filler alloy for brazing

- **Graphite**: IG-430 of Toyo Tanso, **Copper plate**: OHFC, The filler material for the brazing: **TiCuSil alloy** (4.5%Ti-27.7%Cu-68.8%Ag, Wesgo Metals).
- **one-step brazing process** without any surface modification of graphite by selecting the proper filler materials and heat treatments.
- **Pretreatments** were carried out to remove residual gas and impurities in base materials. The graphite was **baked up to 950°C to eliminate the residual gas or water vapor** in the pore of the material. This step is crucial for the sound joining because the residual water vapor or gases deteriorate the wetting layer of the filler alloy during the brazing heat treatment.
- The base material (the graphite and the Cu) and the filler materials (the TiCuSil alloy) are placed in vacuum furnace for brazing process as shown in Fig. 9. These assemblies are heat-treated in **vacuum furnace of $\sim 10^5$ torr**. Tight atmospheric control is necessary because the graphite easily oxide in high temperature.

3. 2 The brazing procedure

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-The curve for the **brazing heat treatment** is shown in Fig. 10.

-The solidus temperature of the TiCuSi1 filler alloy is 780°C, and the liquidus temperature is 900°C. **Both solid and liquid phases of the filler alloy exist in the temperature range between the solidus and the liquids.**

-The assembly slowly heats up to 730°C and maintained for 3 hours **to promote the diffusion bonding** between filler alloy and Cu.

-**To have enough wetting of the filler materials** to the base materials, the assembly was hold for 2 hours at 850°C.

-The assembly was heated up to above the liquidus to 915°C for a short time (10 min.) to **fully impregnate the filler alloy** into the base materials.

3.3 Brazing results

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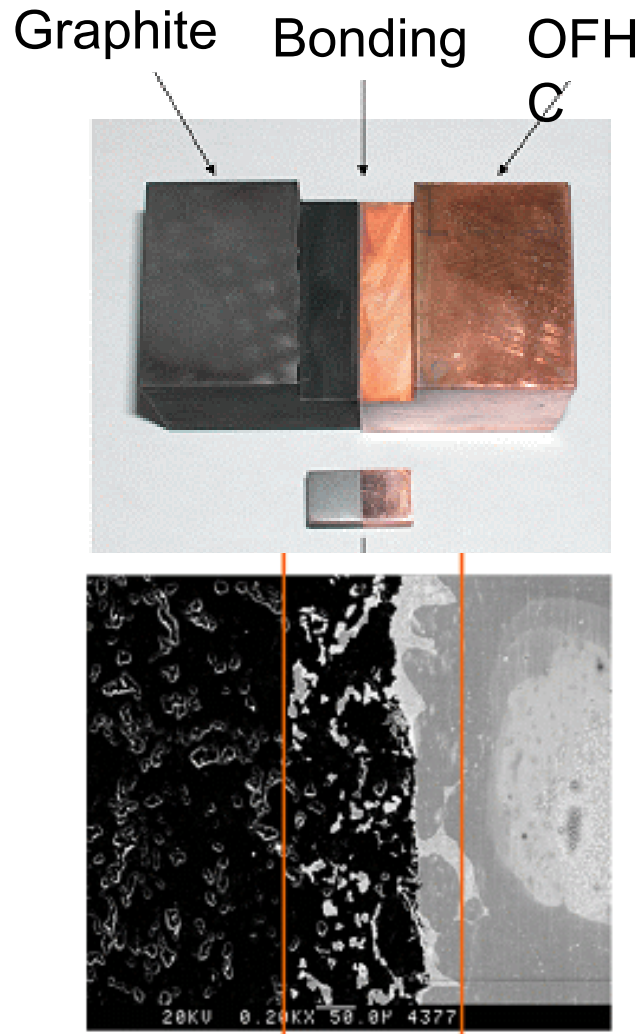


Fig. 11 Microstructure of the joining interface of graphite and copper

-**Brazing results** is shown in Fig. 11.

-The filler alloy **wetted well into the base materials**. The filler alloy flowed into the pore of graphite and made a sound mechanical bonding.

-**An active reaction** of Ti component of the filler alloy can increase the bonding strength between the filler and the graphite.

-**A diffusion bonding** strengthens the joining of the filler alloy and the copper metal.

4. Verification tests

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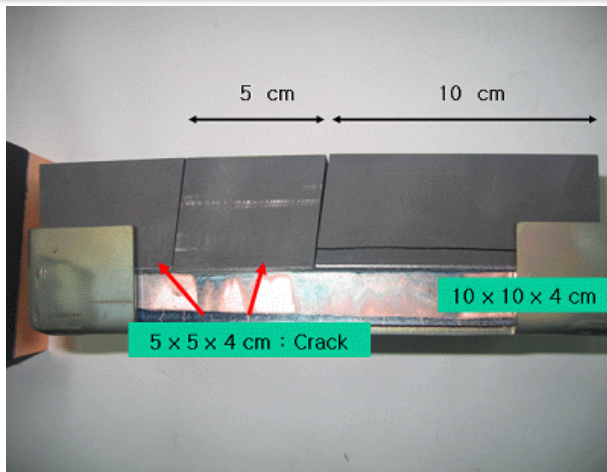


Fig. 12 Cracks in the various size of graphite and Cu tiles.

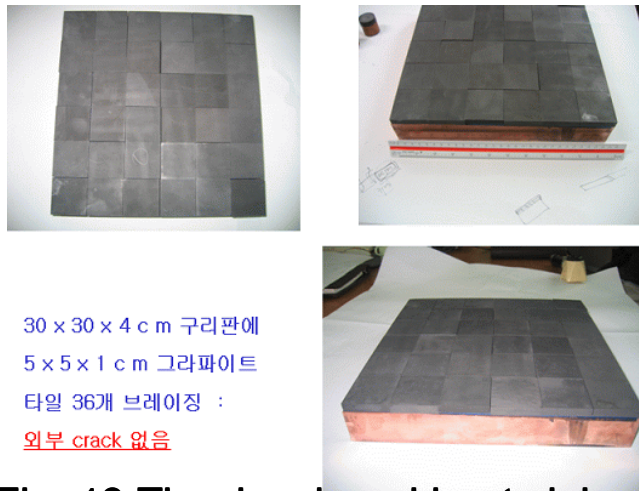
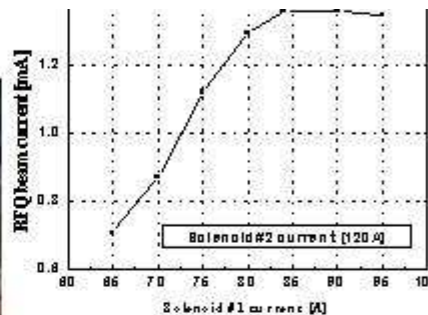
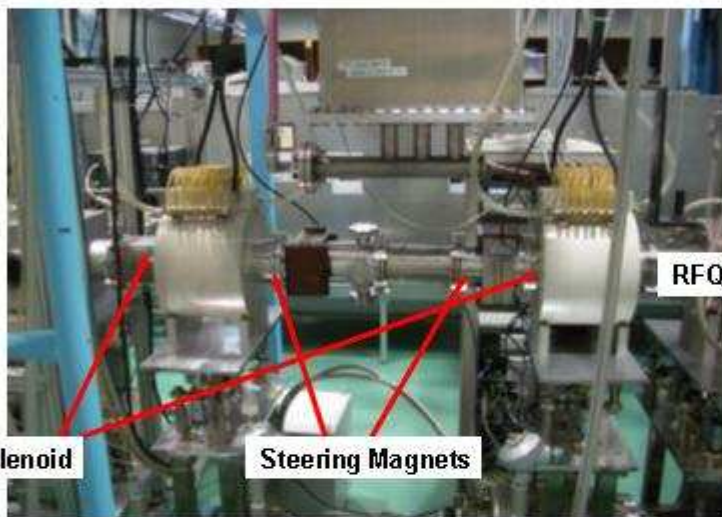


Fig. 13 The developed heat sink structure of beam dump for 20 MeV proton accelerator.

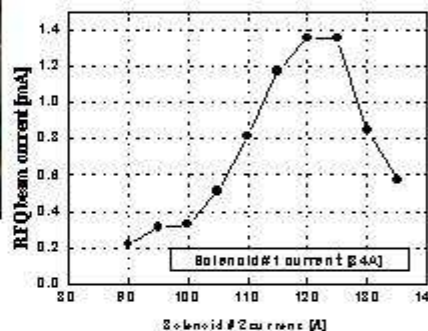
- Various size of brazed assemblies were prepared and investigated to evaluate the mechanical reliability of the assemblies.
- A severe long crack : 10(w) x 10(l) x 4(t) cm, 5(w) x 5(l) x 4(t) cm (Fig. 12).
- No crack: 5 x 5 x 1 cm → heat sink structure materials.
- One heat sink plate which was manufactured by brazing the graphite tiles (36 tiles) to a copper plate (30 cm x 30 cm x 4 cm) is shown in Fig. 13.
- No crack was found in the heat sink plate. We used the plate as one plate of our heat sink structure of beam dump.
- The soundness of the heat sink structure of the beam dump was checked by the thermal fatigue tests with the repetitive heating and cooling between 50C to 200C. It was confirmed that there is no crack in the tested specimens.

- We designed and manufactured the heat sink structure for a beam dump for a 20 MeV proton accelerator.
- The stress, the heat and the radioactivity analyses confirmed the reliability of the developed heat sink structure.
- The heat sink structure was manufactured by brazing a graphite tile to copper plate. One step brazing process was established during the development of the heat sink structure in this study.
- The mechanical soundness was confirmed by the thermal fatigue tests.
- The heat sink structure can be applied to various components, such as plasma facing components, collimators of a accelerator and dumps for resolving high heat load and high radioactivity issues.

Injector

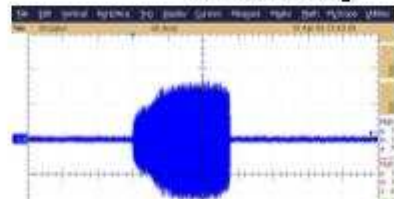
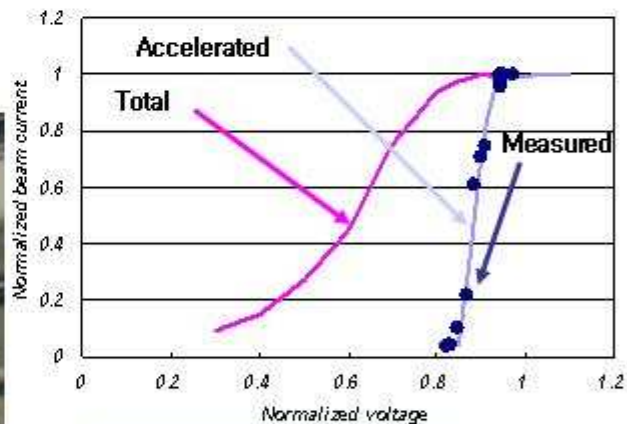


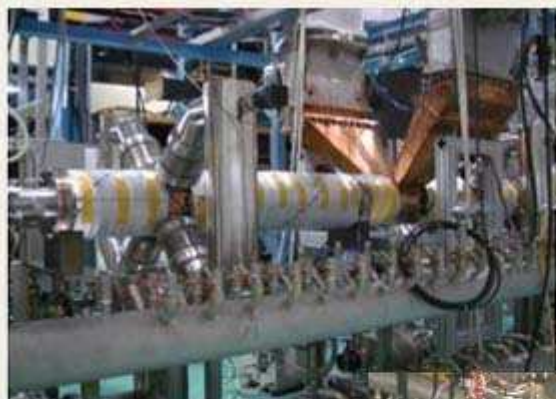
RFQ beam depending on sol#1



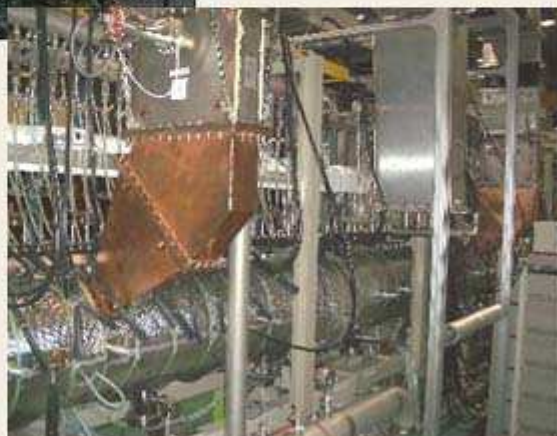
RFQ beam depending on sol#2

[RFQ Beam Experiment]





3 MeV RFQ



20 MeV DTL-1

