國家同步輻射研究中心
National Synchrotron Radiation Research Center

AFAD Asian Forum for Accelerators and Detectors 2023
12-14 April 2023

Operational experiences of two CPMUs at NSRRC

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Cryogenic Permanent Magnet Undulators

High-brilliance X-rays can be obtained from short-period undulators with small phase errors installed in third-generation synchrotron radiation facilities,

- Shorter wavelength radiation

→ Hard X-ray

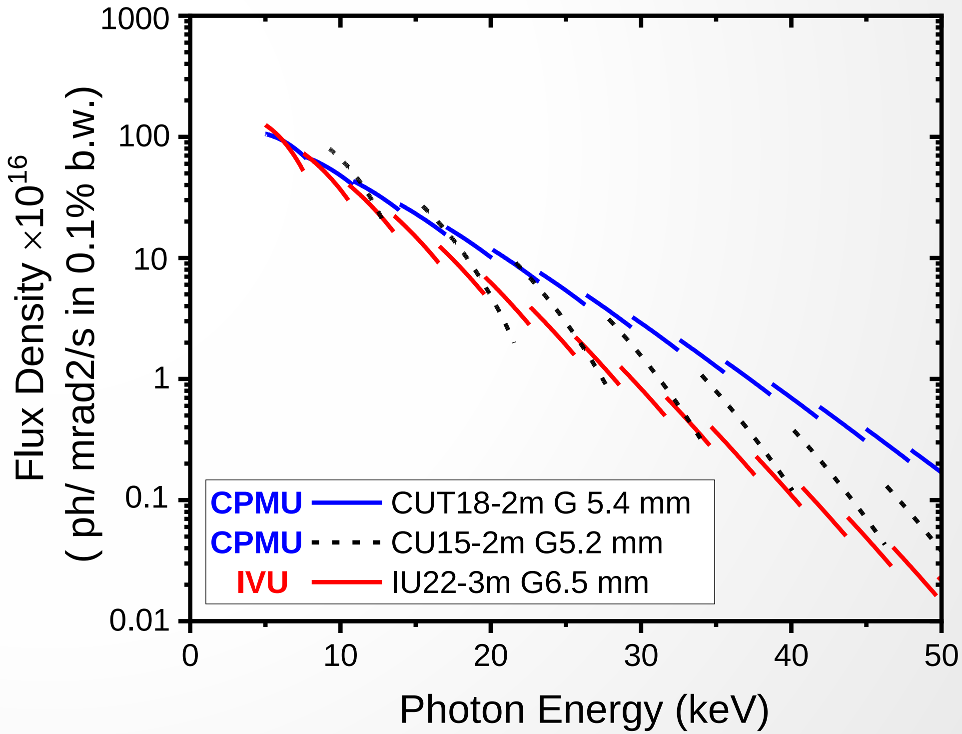
- More periods for a fixed length

→ High Coherent Photon Flux

- Low degradation of SR from small phase errors of an undulator

→ Higher Harmonics

A cryogenic permanent magnet undulator (CPMU) can provide all these characteristics.



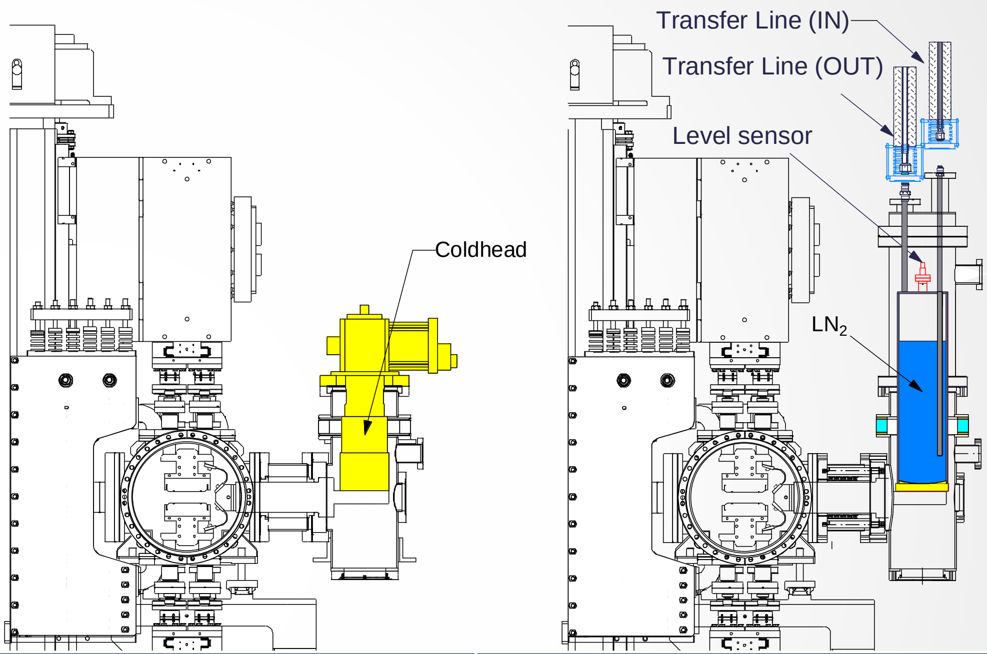
CPMUs at Taiwan Photon Source

CU15-2m	VS.	CUT18 -2m
Hybrid magnetic structure $Pr_2Fe_{14}B$ + Dy (NMX-68CU) Vanadium Permendur Cryo-cooler cooling		Hybrid magnetic structure NdFeB +Tb (NMX-U52SH) Vanadium Permendur LN_2 tank cooling
1.41 at 300 K 1.64 at 80 K	Remanence (T)	1.47 at 300 K 1.57 at 170 K
1740 at 300 K 6385 at 80 K	Coercivity, *Hcj* (kA/m)	1441 at 300 K 2854 at 170 K
15	Period length (mm)	18
5.2	Min. magnetic gap ,G_m (mm)	5.4
1.01	Effective magnetic field (T)	1.18
1.43	Deflection, *K*	1.98
133	Number of periods	111
24	Magnetic force (kN)	26
83	Operating temp. (K)	170

Cooling Source

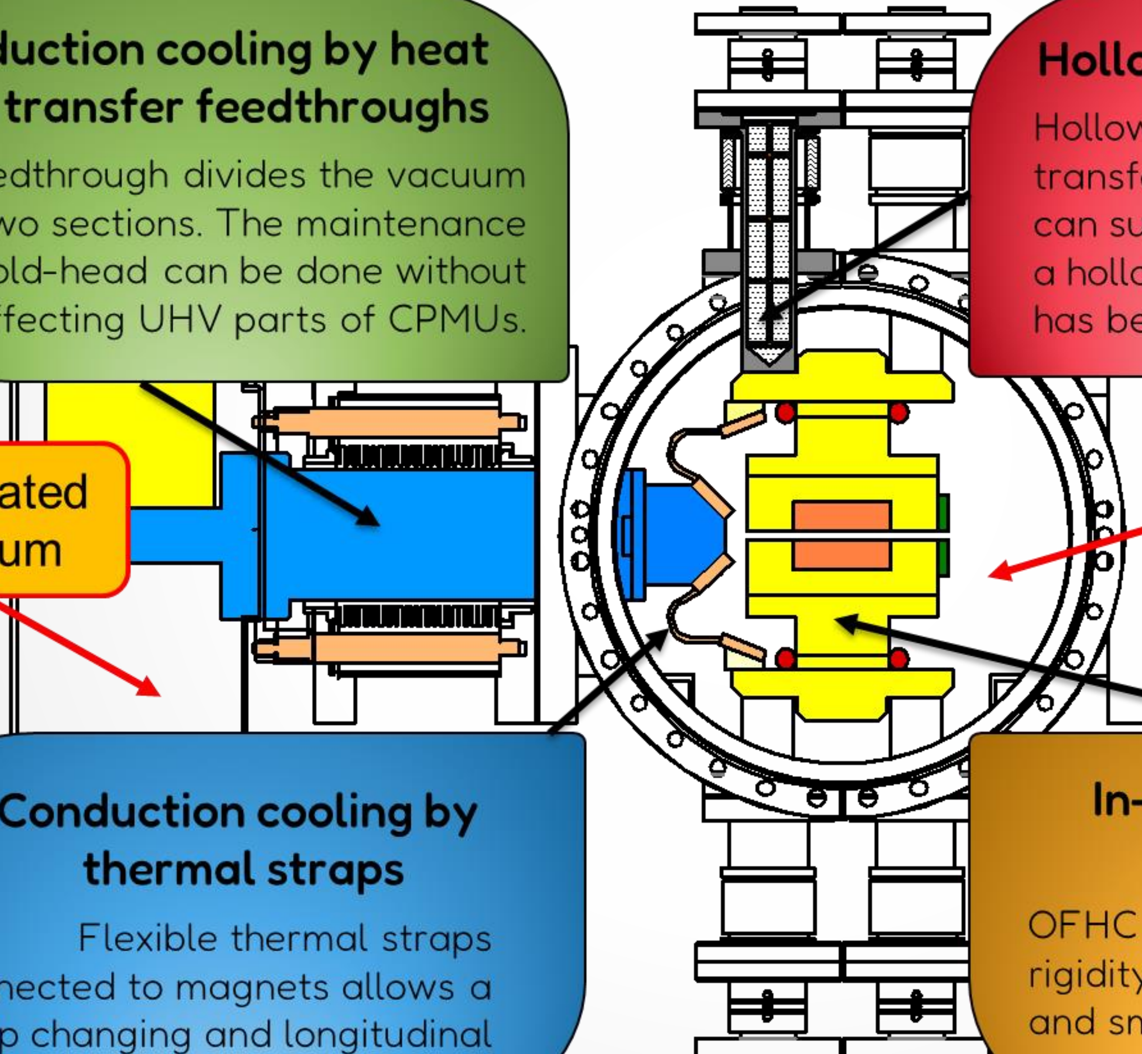
Unique features of TPS-CPMU:
- Conduction cooling of magnet arrays to avoid the damage of the accelerator ultrahigh vacuum (UHV)

- Compatibility with both cryocoolers and liquid nitrogen (LN_2) tanks as a cooling system



Cooling source	Cryo-cooler	Liquid Nitrogen
Lowest temp. of PMs	50 K	115 K
Operational cost at NSRRC	~ $ 2.7 USD / hr (~ 8 kW x 2)	~ $ 0.7 USD / hr (~ 4 L/hr x 2)
Annual maintenance	Yes	Few
Vibration of cooling source	High (but acceptable)	Very Low
Cooling time	18 ~ 24 hrs	40 hrs

Special Design for TPS-CPMU



Conduction cooling by heat transfer feedthroughs

A feedthrough divides the vacuum into two sections. The maintenance of a cold-head can be done without affecting UHV parts of CPMUs.

Hollow type bellows link-rod

Hollow type link-rod reduces heat transfer to 1/5. A bulkhead design can suppress the air circulation of a hollow space. No condensation has been found in operation.

Separated vacuum

Ultra-high vacuum

Conduction cooling by thermal straps

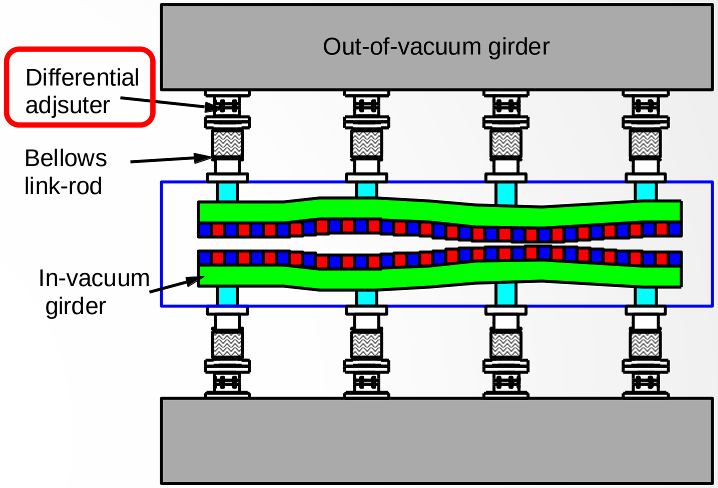
Flexible thermal straps connected to magnets allows a gap changing and longitudinal thermal displacements.

In-vacuum girders by OFHC copper

OFHC copper girders have high rigidity, high thermal conductance, and smaller thermal expansion compared to an aluminum material.

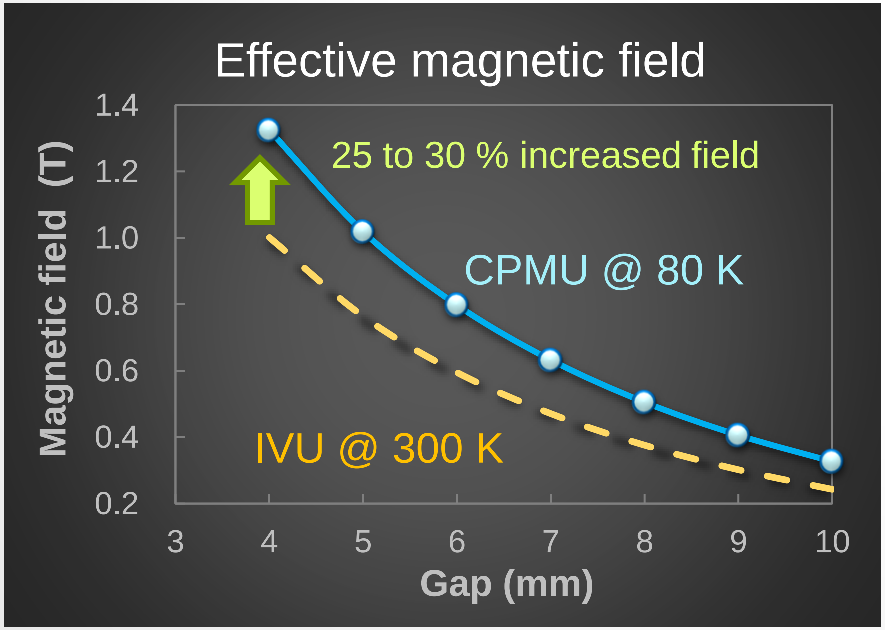
Magnetic performance (CU15)

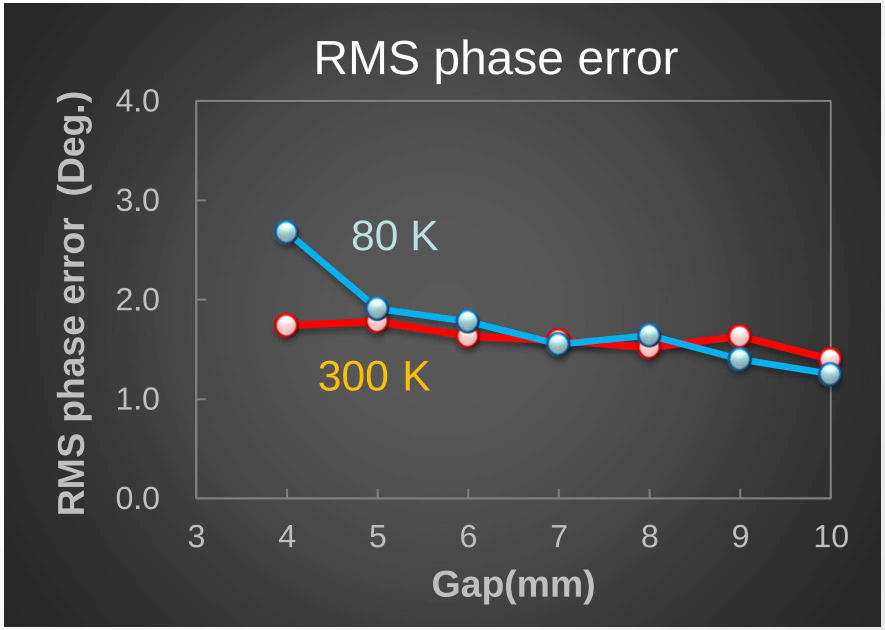
Magnetic field of CPMU is increased by 25 to 30 %, compared to an IVU.



Field errors at 80 K are caused by :

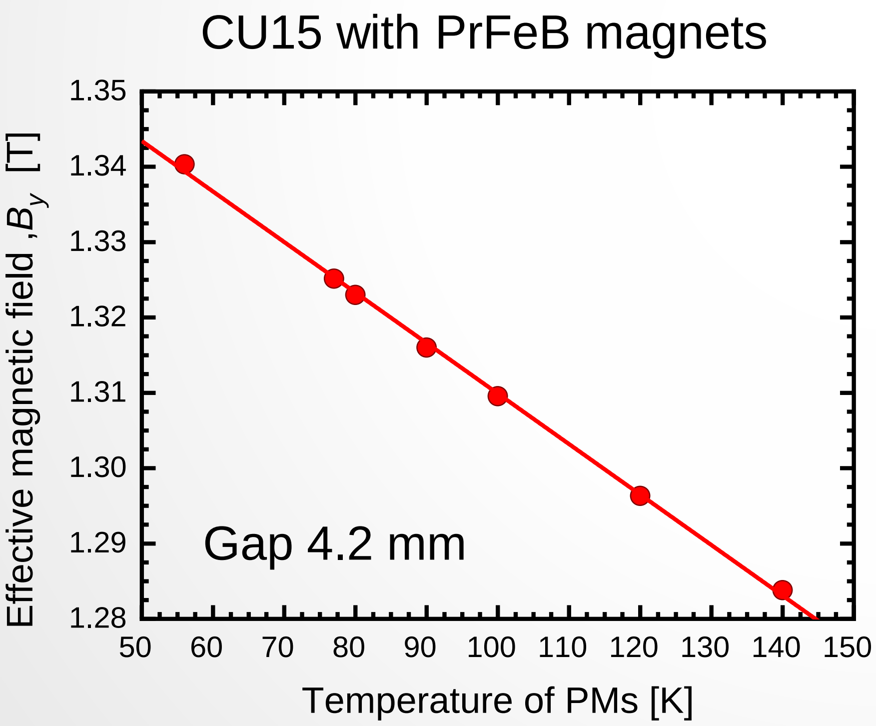
1. Gap errors due to thermal effect
   - Deformation of in-vacuum girders
   - Uneven shrinkage of bellows link-rods
2. Gap errors from increased magnetic forces

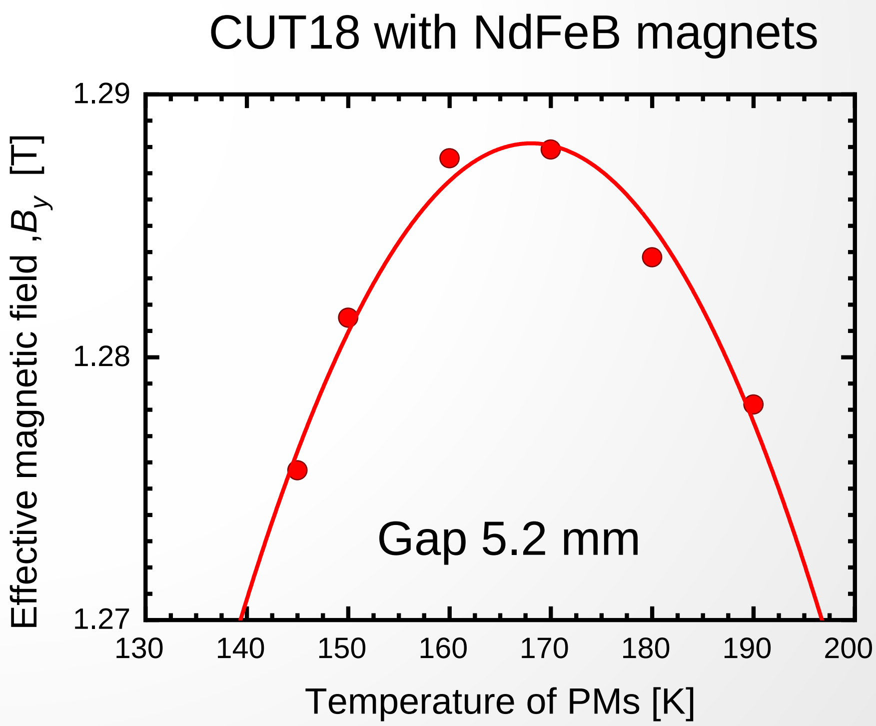




Temperature dependence of field

The temperature dependence of the magnetic field was measured for two CPMUs (CU15 and CUT18): for CU15 with PrFeB magnets, the field increases monotonically with decreasing temperature, whereas for CUT18 with NdFeB magnets, the field reaches a maximum around 170 K.





Cooling margin of CPMUs

- can be measured at zero beam current

The cooling margin is the available power to compensate the beam induced heat-load. The sufficient cooling margin is important to keep a stable temperature control of magnets.

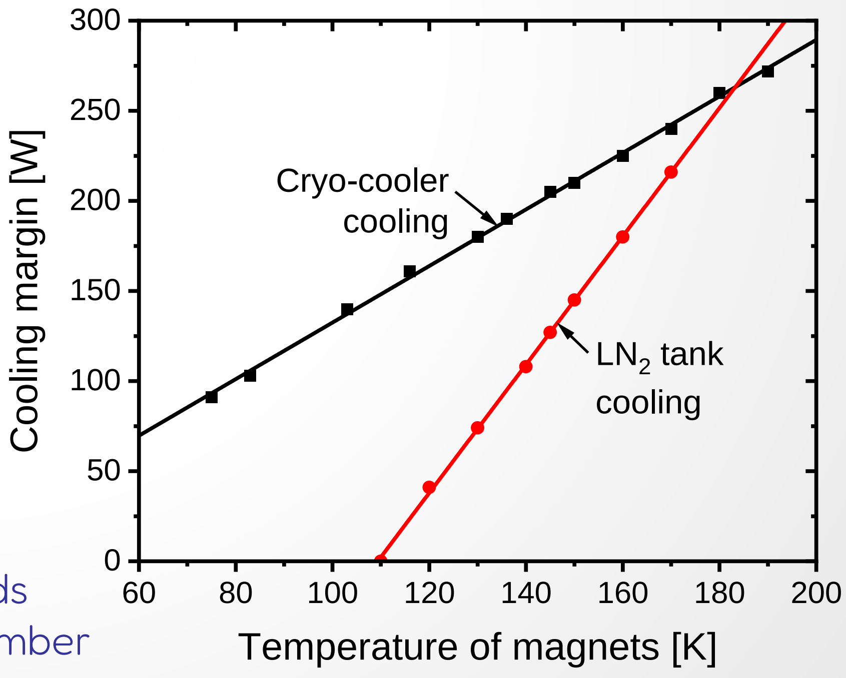
$$P_{margin} = P_{heater}$$

The cooling margin can be measured by heater power at equilibrium without beam current.

$$P_{cooling} = P_{system} + P_{heater}$$

$$P_{system} = P_{cond.} + P_{rad.}$$

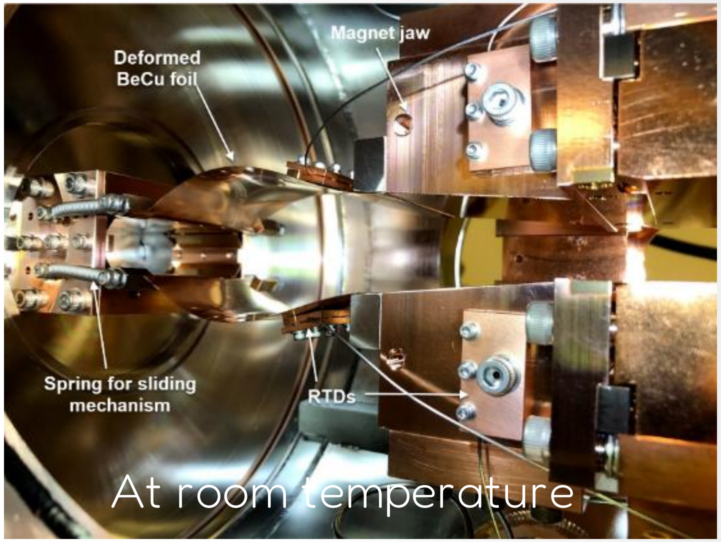
P_{cond}: heat transfer from the bellows-link rods
P_{rad}: thermal radiation from the vacuum chamber



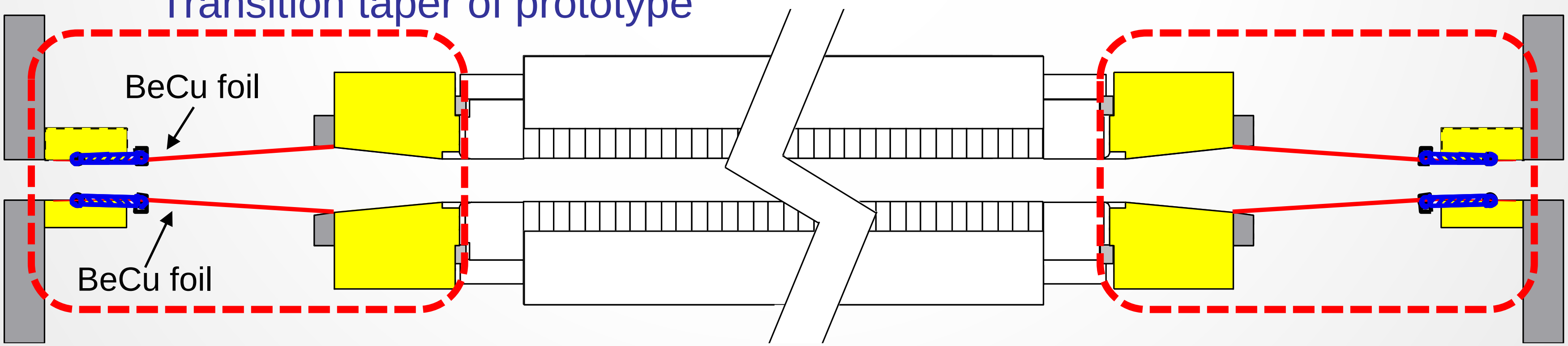
Commissioning of CU15

With beam current up to 500 mA

The first attempt to operate CU15 in the storage ring at a beam current under 300 mA was successful. **However,** when the beam current increased gradually to 500 mA, the equilibrium temperature of magnets and tapers of prototype increased to 256 K and 410 K, respectively.



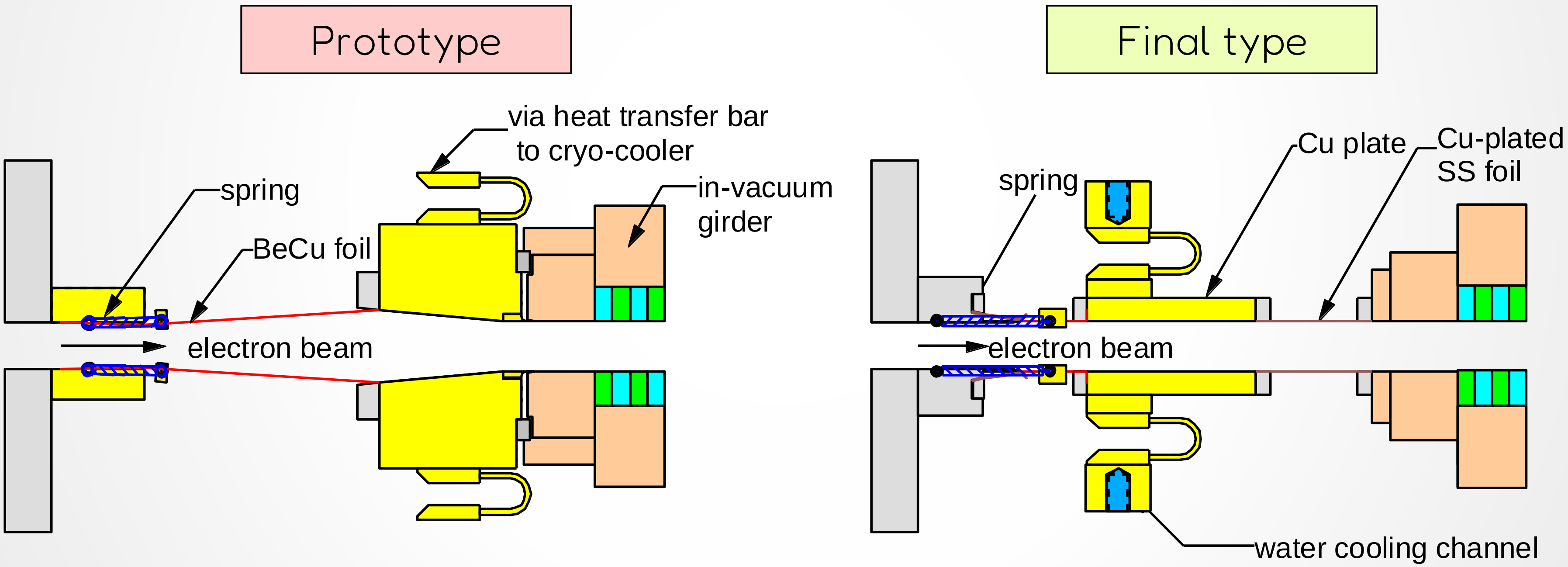
Transition taper of prototype



The BeCu foil deformed as its temperature increased, eventually forming a cavity-like structure. The electromagnetic waves were trapped inside of cavity-like structure to cause energy loss and beam heating.

Transition Taper Design

The tapers at both ends of CPMUs need to be flexible to allow for gap variation and low thermal conductivity to reduce heat flow from the vacuum chamber to the magnet arrays.



A water-cooled section is added to the final type to accommodate heat load derived from geometric impedance. At present, this design can ensure the CU15 operation at beam current of 500 mA and gap of 5 mm without any problem.

Beam-induced Heat-load

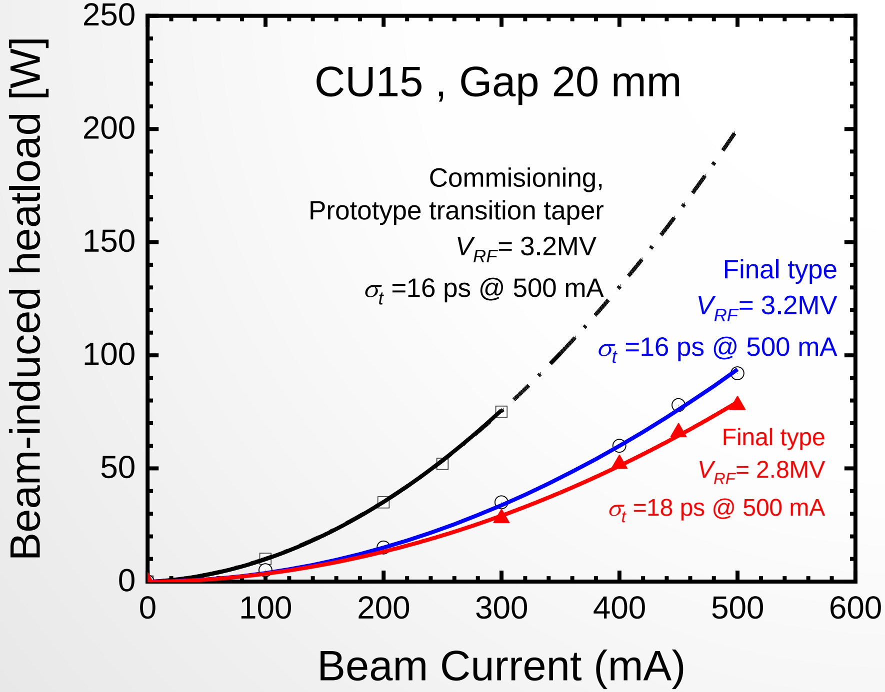
With beam current up to 500 mA

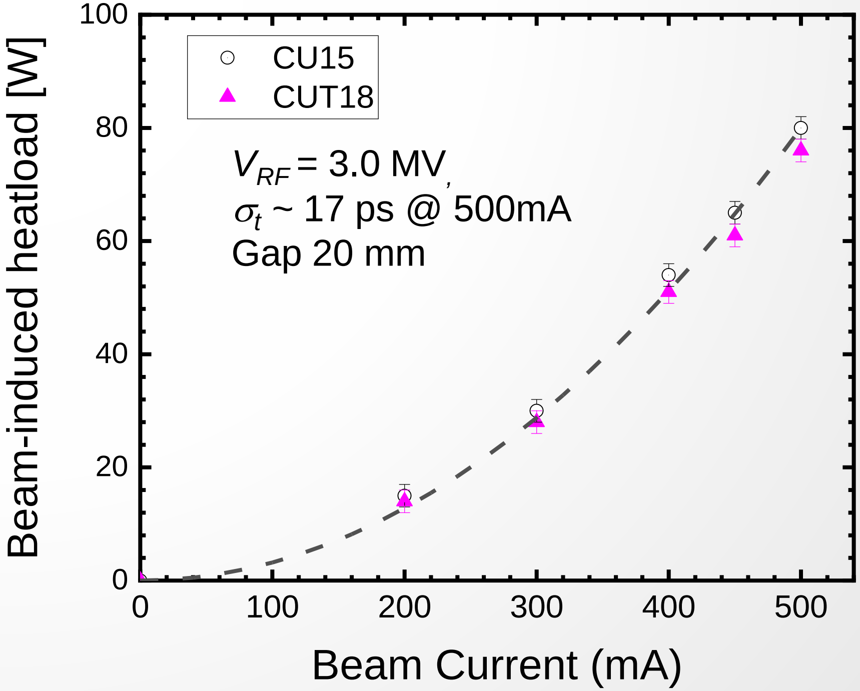
Additional heating derived from the electron beam can be traced from the change of the heater power.

$$P_{beam} = P_{margin} - P_{heater}$$

The beam-induced heat-load decreases with increasing bunch length, σ_t .

The bunch length, σ_t, increases with decreasing RF voltage, V_{RF}.





Summary

- Two CPMUs with magnetic and cryogenic performance above the required specifications have been successfully developed at the TPS, NSRRC.
- Unique features of cryogenic system at TPS-CPMUs are conduction cooling of magnet arrays to avoid damage to the accelerator ultra-high vacuum, and compatibility with both cryocoolers and liquid nitrogen tanks as a cooling source.
- With a temperature control system, the temperature of magnets can be stabilized, and the CPMUs can provide stable, reproducible photon energy spectra.
- The main heat-load at CU15 / CUT18 is derived from broadband impedance including resistive wall heating and geometric impedance from taper/step structure.
- The photon flux at 20 keV using the CU15-2m is 3 times higher than that using the IU22-3m. The experimental time can efficiently decrease to one third on replacing IU22 with CU15.


Thank you
very much !
CU15 operated at
Taiwan photon Source
NSRRC
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