# Cryogenic Permanent Magnet Undulator

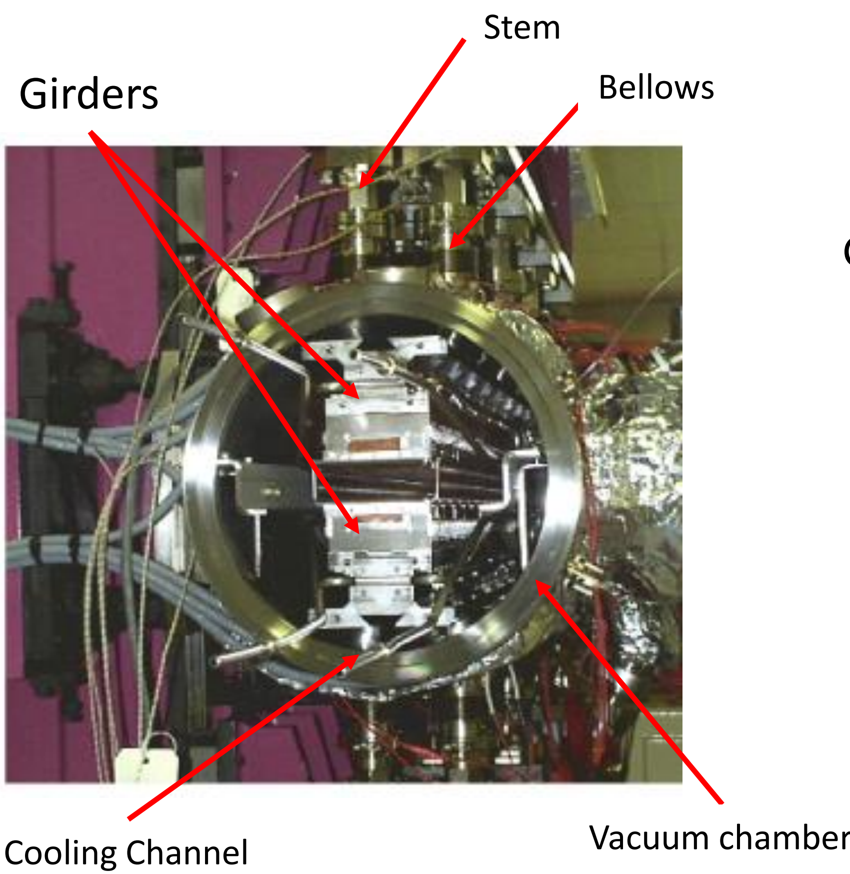

- C. Kitegi
- J. Rank
- T. Tanabe
- J. Chavanne
- G. Lebec
- C. Penel
- F. Revol

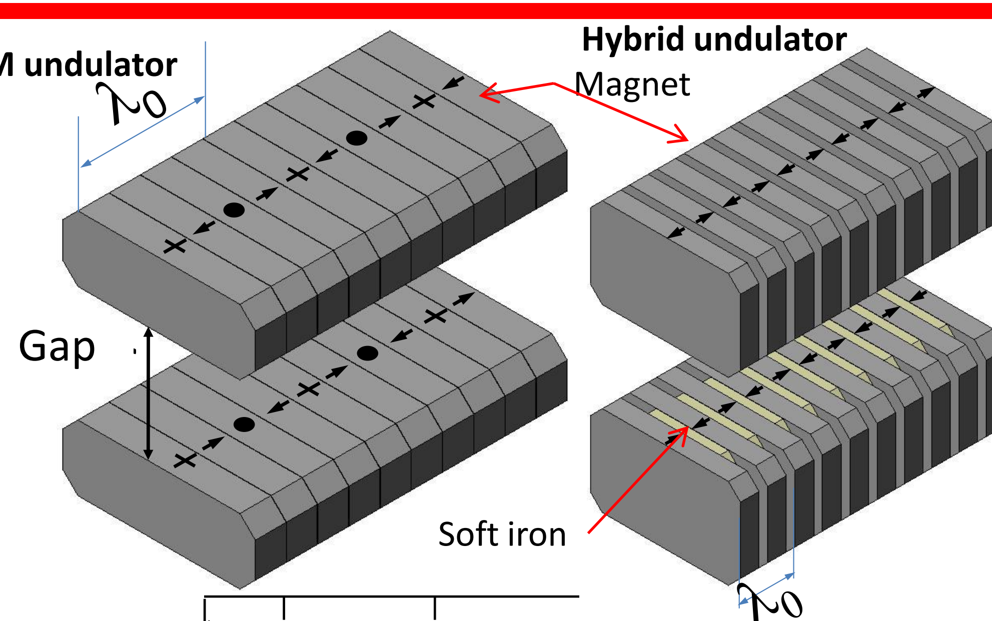
# Outline

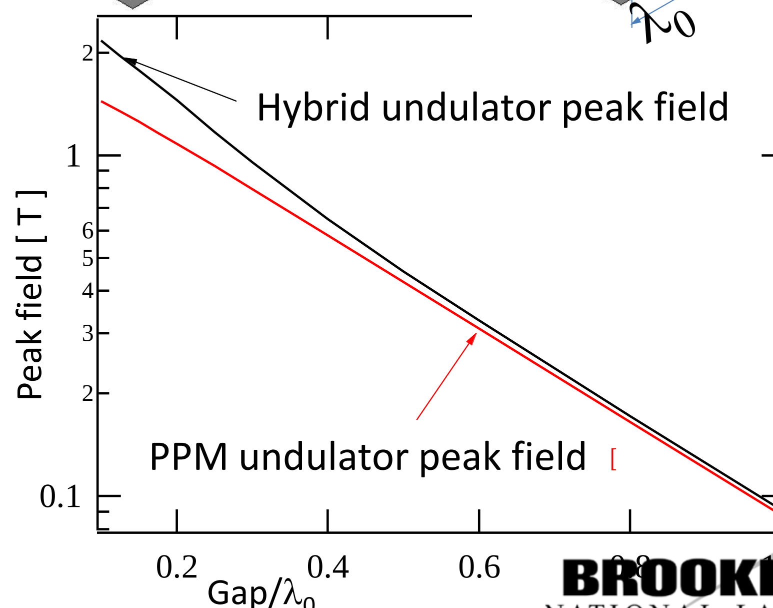
- IVU
- Magnetic materials for IVU
- ESRF CPMU
- NSLS-II CPMU

# In-Vacuum Undulator (IVU)

T. Hara, J. Syn. Rad. 1998




**For a small ratio Gap/$\lambda_0$ the hybrid undulators produces a stronger peak field than PPM undulators**

# Permanent magnets for IVUs

•**GeV e-, γ, N**: At small gap values, demagnetization may occur.
•IVU are baked at high temperature (~140K) to ensure a high vacuum compatibility.

⇒One chooses magnet with strong resistance to demagnetization.
⇒For any magnet family, resistance increases with coercive field.

### $Sm_2Co_{17}$

- Strong resistance to demagnetization
- Remanent field limited to 1.05 T

### $Nd_2Fe_{14}B$

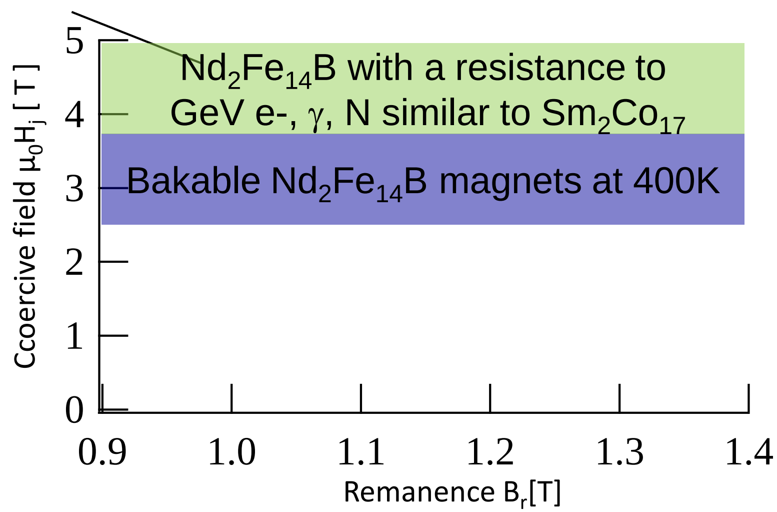
- High remanent field (up to 1.4T)
- Poor resistance to demagnetization
- Possible to choose magnets with high coercive field then remacence <1. 2T

### $Pr_2Fe_{14}B$

- So far only specific commercial offers

T.Bizen, Nucl. Inst. Meth. Phys. Res. 2001

J. Chavanne, EPAC 2002

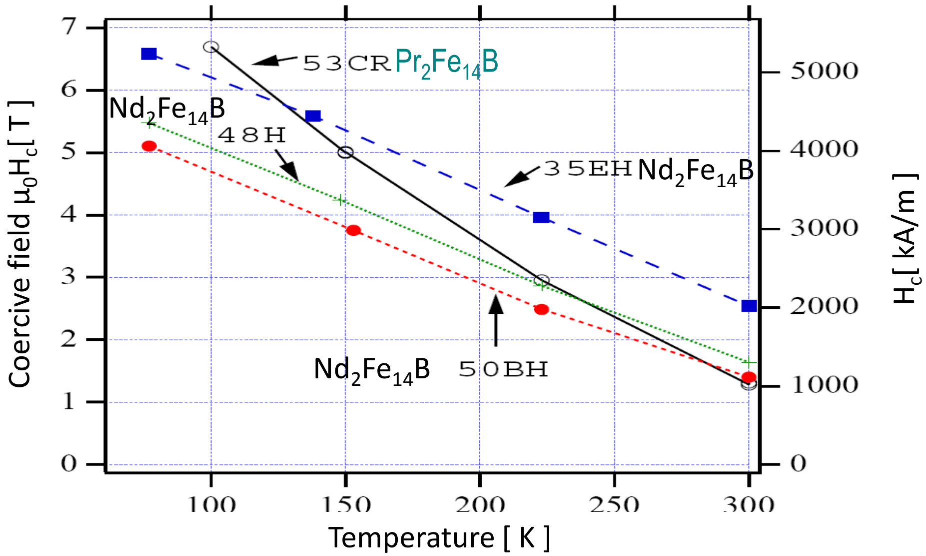


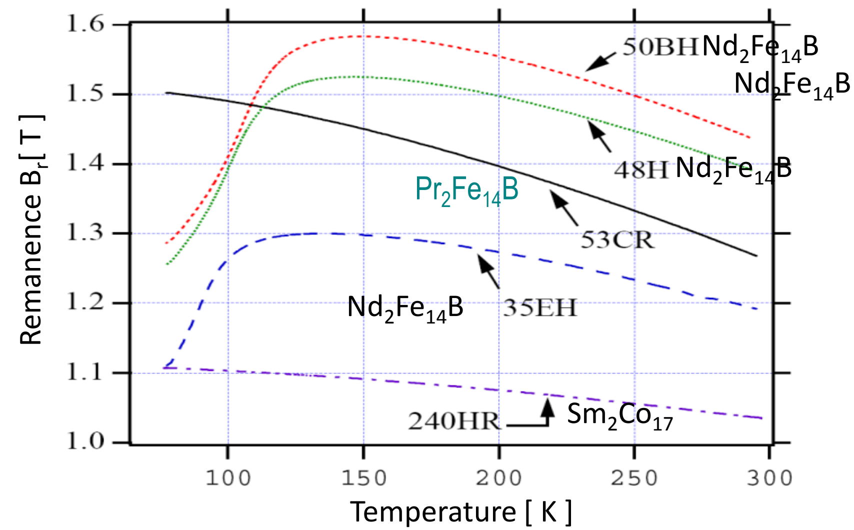

However …

# Permanent magnet cooled at cryogenic temperature

Cool magnets at cryogenic temperature increases their **coercive field** and **their remanence**

T. Hara, APAC 2004




At low temperature $Nd_2Fe_{14}B$ magnet resistance ~ $Sm_2Co_{17}$ magnet (T. Bizen EPAC04)

**A low temperature « new magnets »**

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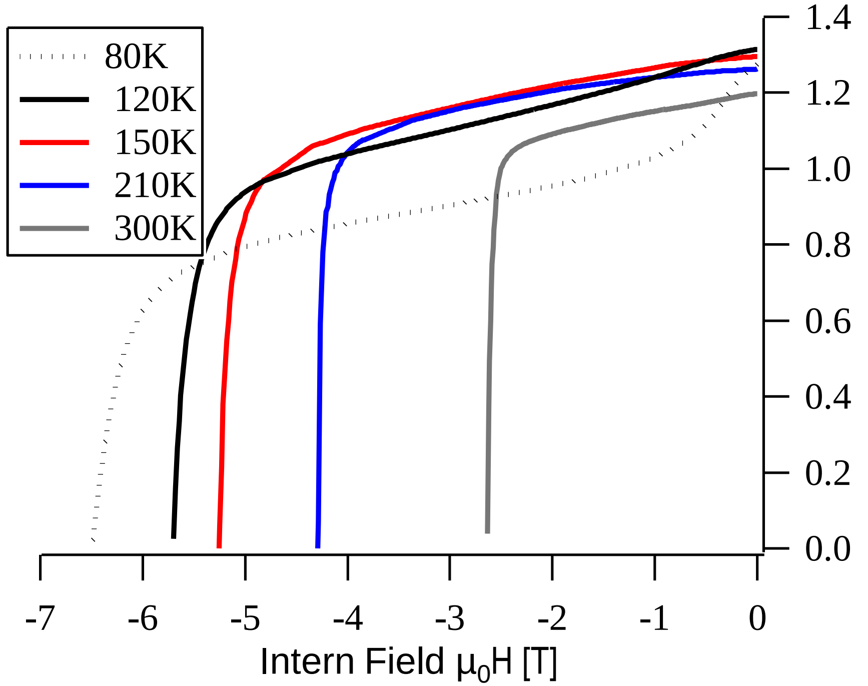
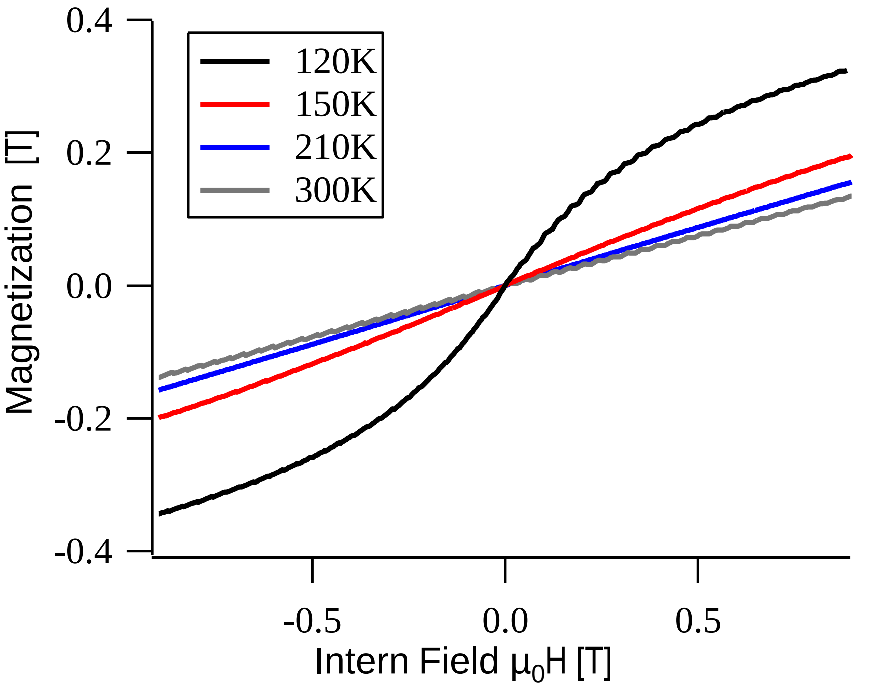
# NdFeB magnetization curve at cryogenic temperature

NEOREM magnet 495t
Measurments performed at the Louis Néel laboratory (Grenoble-France)
Size of samples 4×4×4mm³ et 4×4×1 mm³

**Magnetization curve parallel to the easy axis**




**Magnetization curve perpandicular to the easy axis**

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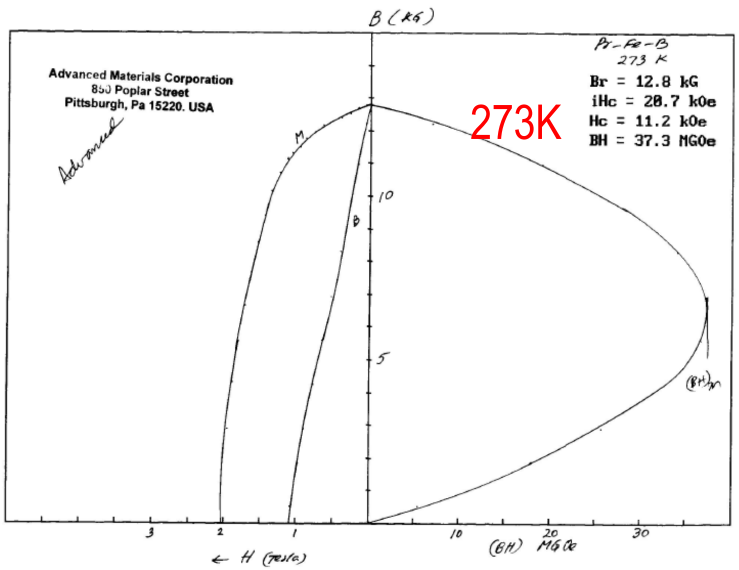
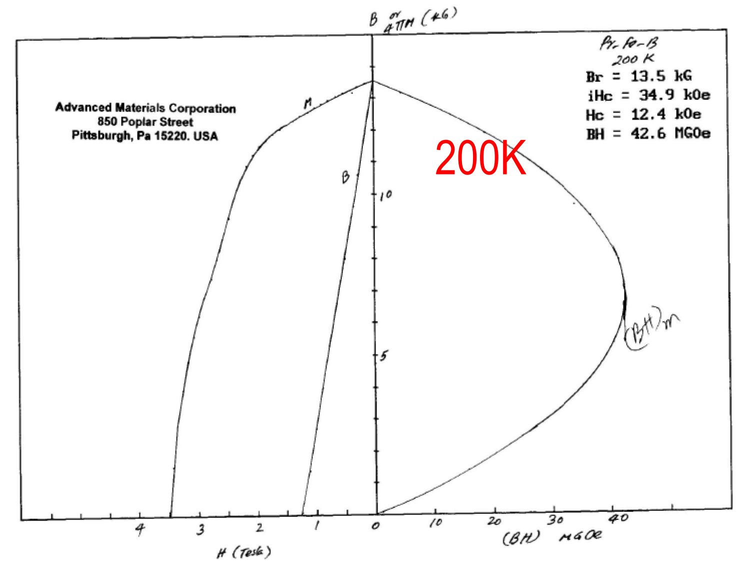
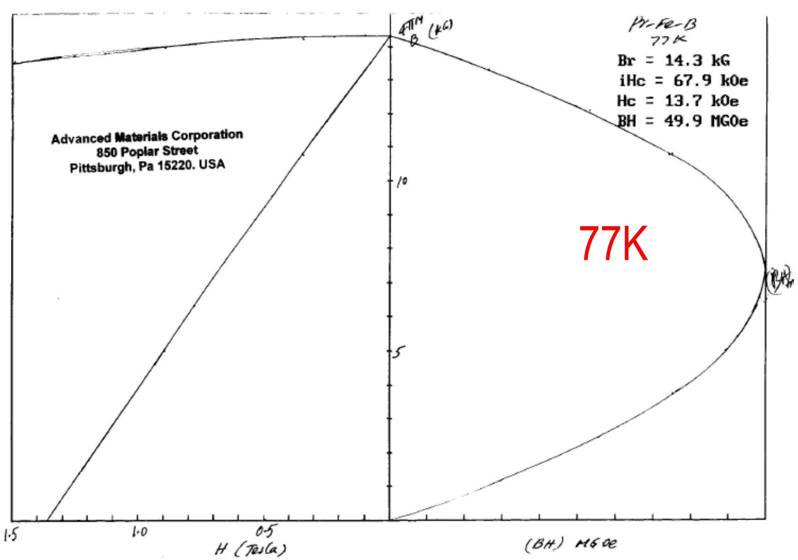
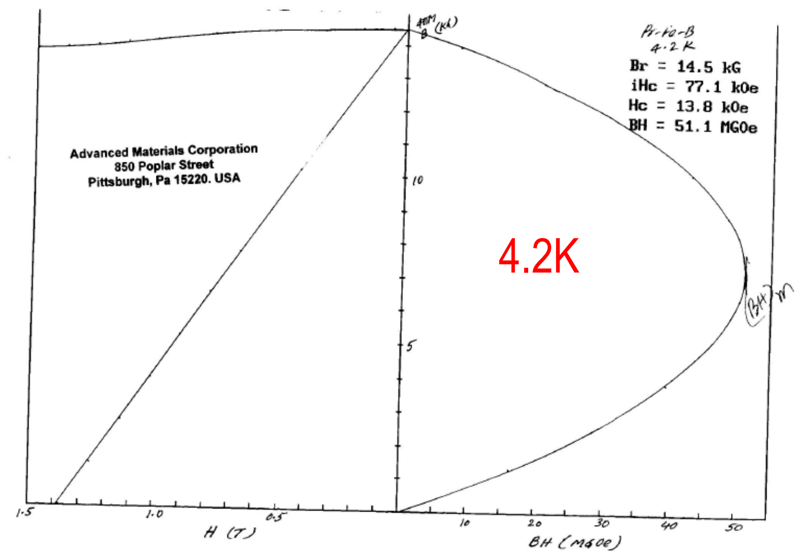
# PrFeB magnetization curve at cryogenic temperature



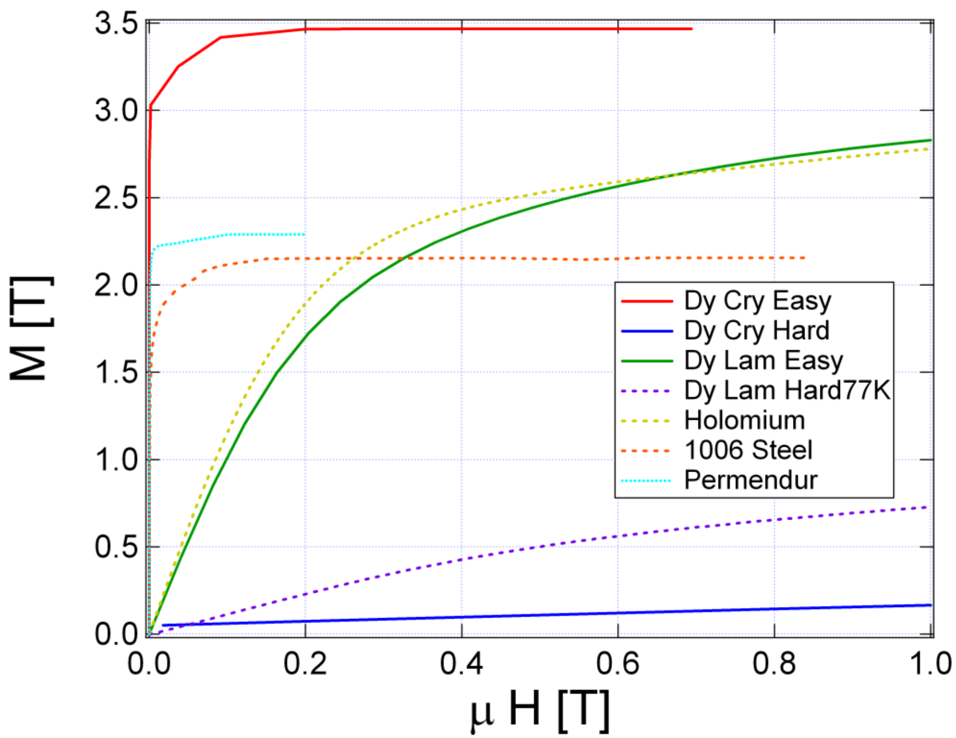



# New Pole Materials

- Crystallized Dysprosium has high saturation limit and high permeability in a low field




- Dy measured data by BNL (courtesy by Slowa Solovyov )
- Holomium measured data by NSRRC (courtesy by Ching-Shiang Hwang)
- 1006 Steel data by a vendor
- Permendur measured data by NEOMAX

# Cryogenic Permanent Magnet Undulator

| Lab | Year | PPM/Hyb. | Magnet | Period [mm] | Deflexion parameter | Length [m] |
|---|---|---|---|---|---|---|
| SPring-8 | 2004 | PPM | $Nd_2Fe_{14}B$ | 15 | 1.3 | 0.6 |
| NSLS/ADC | 2005 | Hyb | $Nd_2Fe_{14}B$ | 18 | 1.62 | 1 |
| SLS/ SPring-8 | 2007 | Hyb | $Nd_2Fe_{14}B$ | 14 | ? | 2 |
| ESRF (I) | 2004 | Hyb | $Nd_2Fe_{14}B$ | 18 | 1.5 | 2 |
| ESRF(II) | 2009 | Hyb | $Nd_2Fe_{14}B$ | 18 | 1.6 | 2 |
| DIAMOND/Dan fysik | 2009 | Hyb | $Nd_2Fe_{14}B$ | 17.7 | 1.7 | 2 |
| SOLEIL | 2008 | Hyb | $Pr_2Fe_{14}B$ | 18 | 1.95 | 2 |
| NSLS | 2009 | Hyb | $Pr_2Fe_{14}B$ | 19 | 2.02 | 3 |

# Cryogenic system

**Principle:** Pressurized liquid nitrogen flows into a closed loop cooled by a liquid nitrogen bath at atmospheric pressure

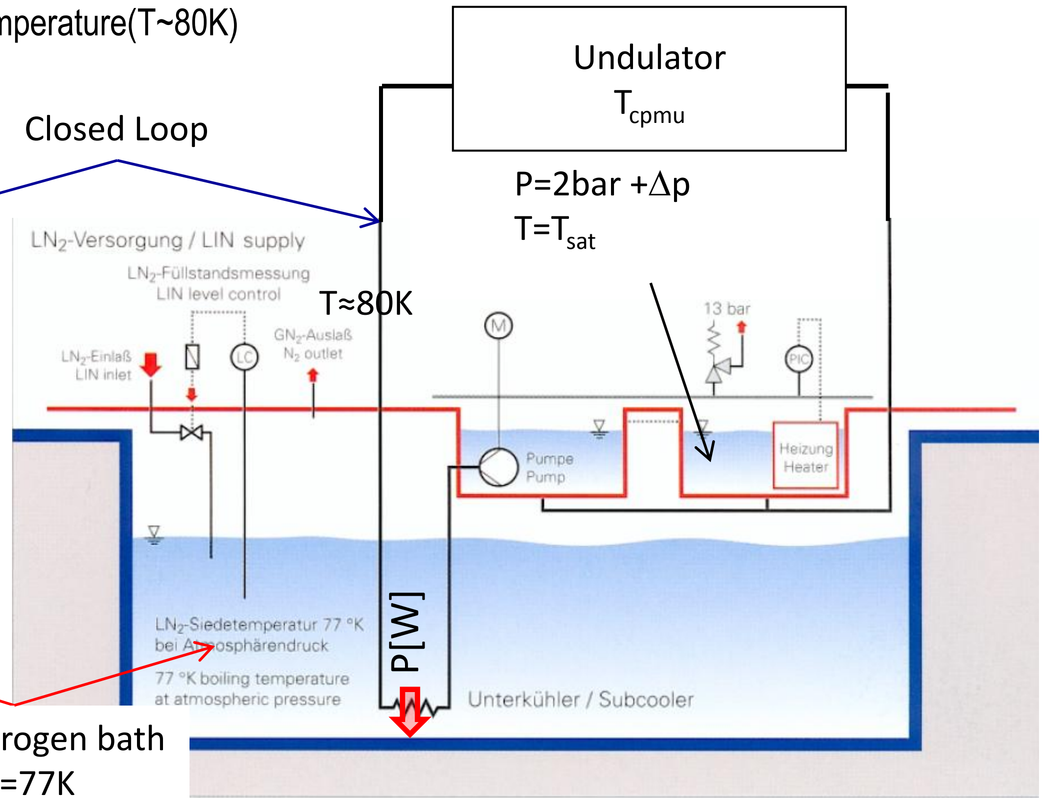
**Advantages**

Well known at the ESRF, used to cool monochromators (internal expertise and technical support)

Well adapted for large system  and  large frigorific capacity 2kW

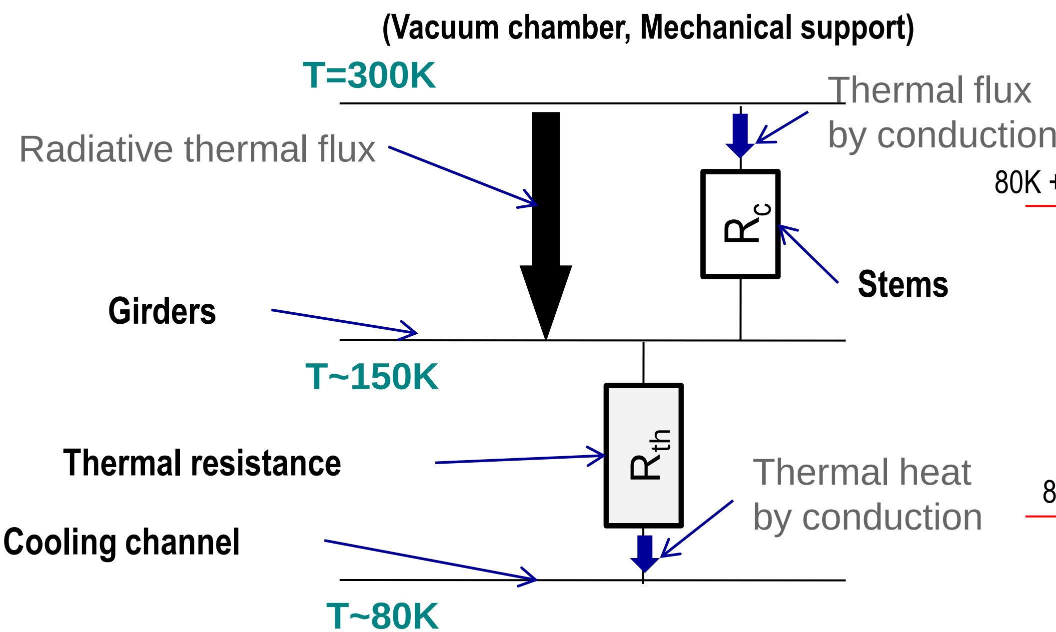
**Drawbacks**

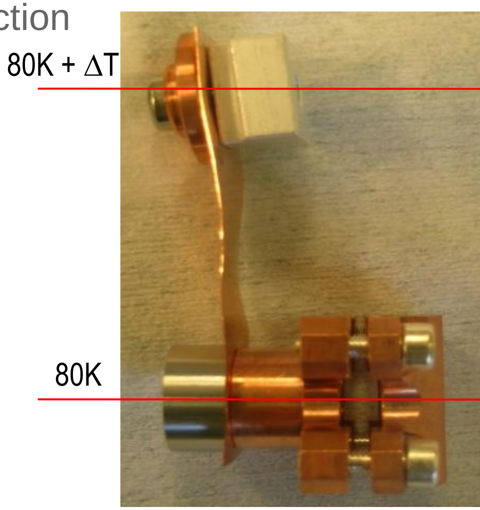
The liquid nitrogen bath at atmospheric pressure fixes the temperature(T~80K)

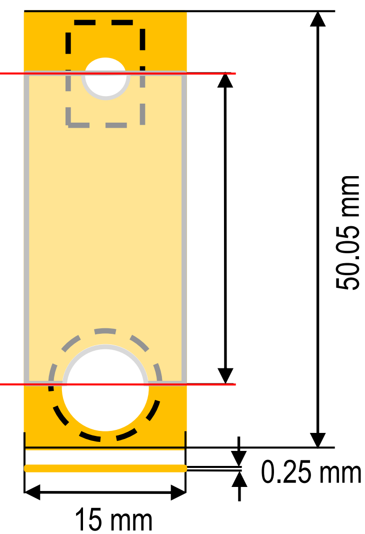


# Cooling CPMU based on NdFeB magnets around 150K

Control the thermal contact between the undulator and the liquid nitrogen loop with thermal resistances.




Cool the undulator at the temperature implies to:

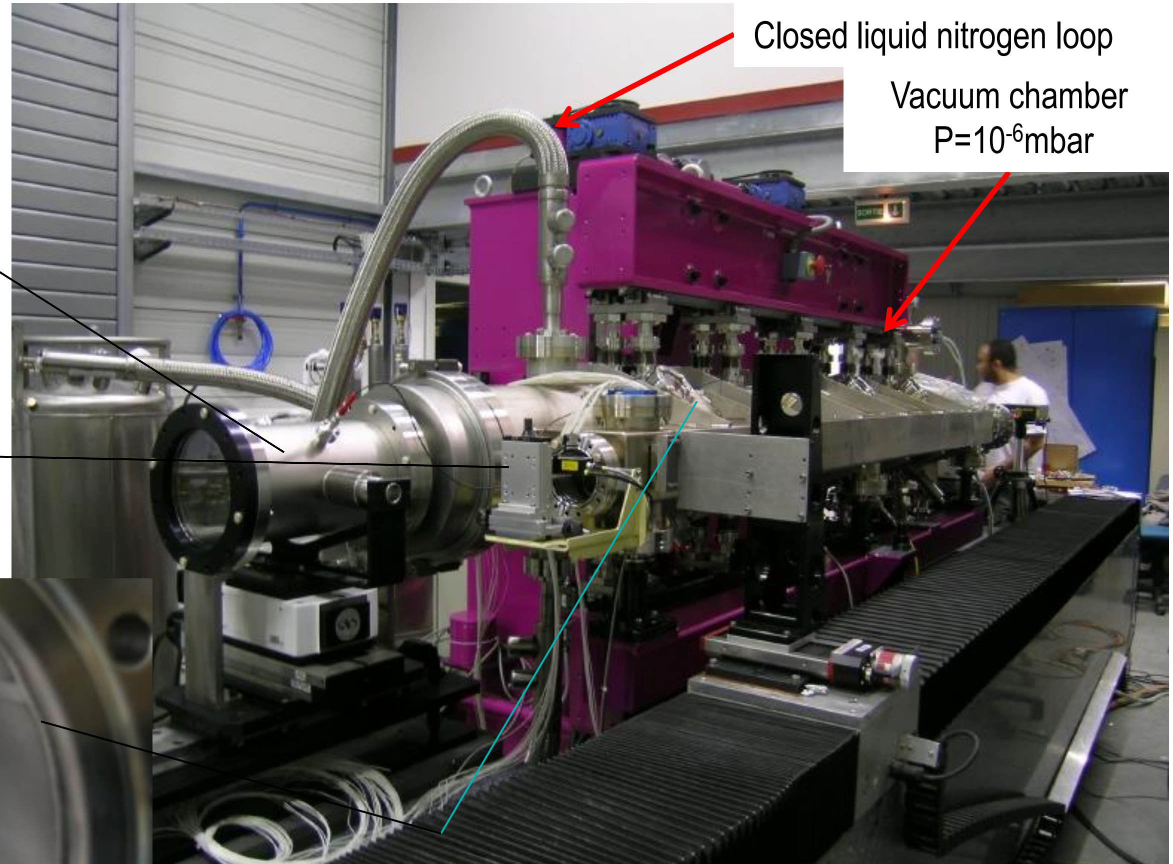
- To compute the thermal resistance $R_{th}$
- To measure the thermal flux $\phi$ to evacuate

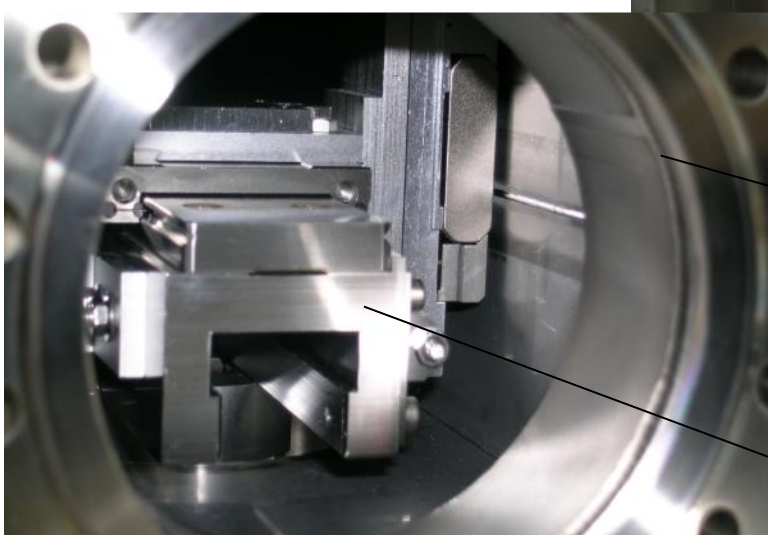
$R_{th}$ depends on:

- The resistance geometry
- The thermal conductivity of copper

$R_{th}$= 15.6 K/W

# In vacuum magnetic measurement bench





Closed liquid nitrogen loop

Vacuum chamber
P=10$^{-6}$mbar

Stretched wire
Field integral measurement

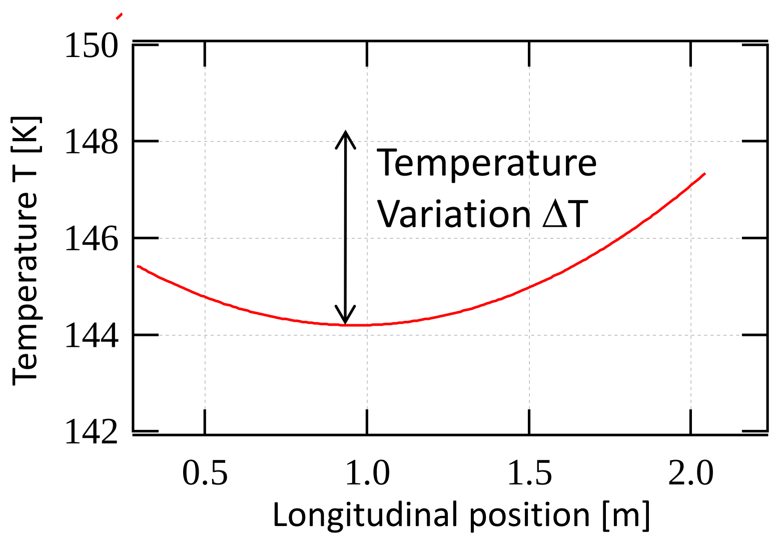
Laser

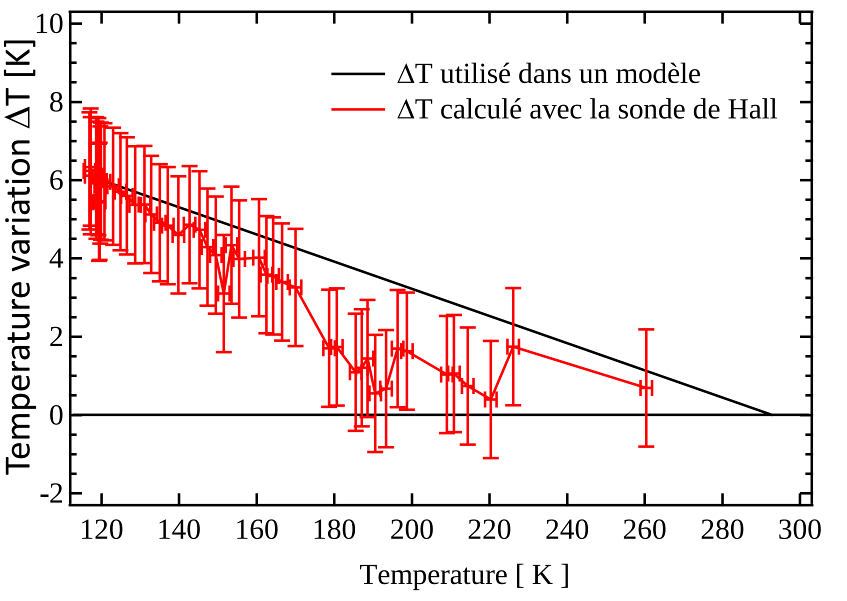
Hall probe motorization:
-In air
-Magnetic coupling

Rail

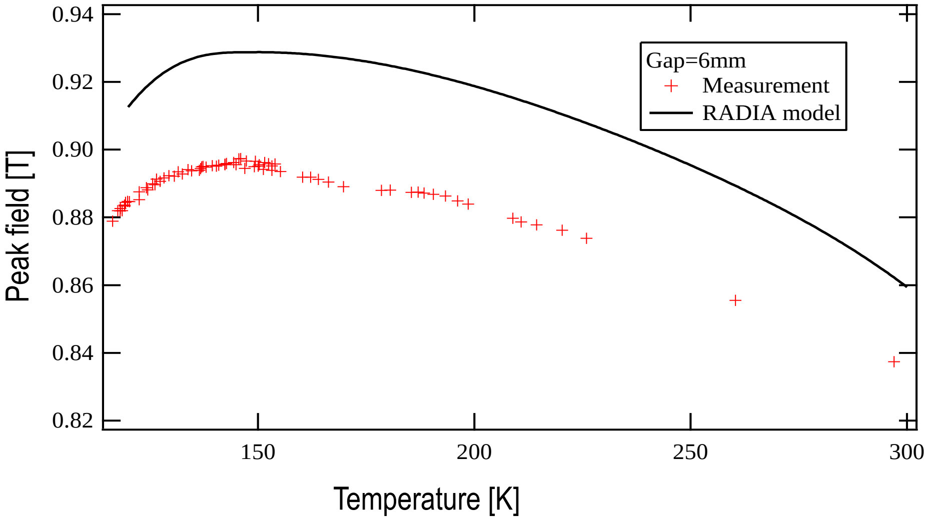
# Temperature variation along girders

- Temperature variation determined at each local field measurement
- Temperature not uniform along girders
- Temperature variation increases at lower temperatures
- Gradient arises from bad connection at undulator extremities



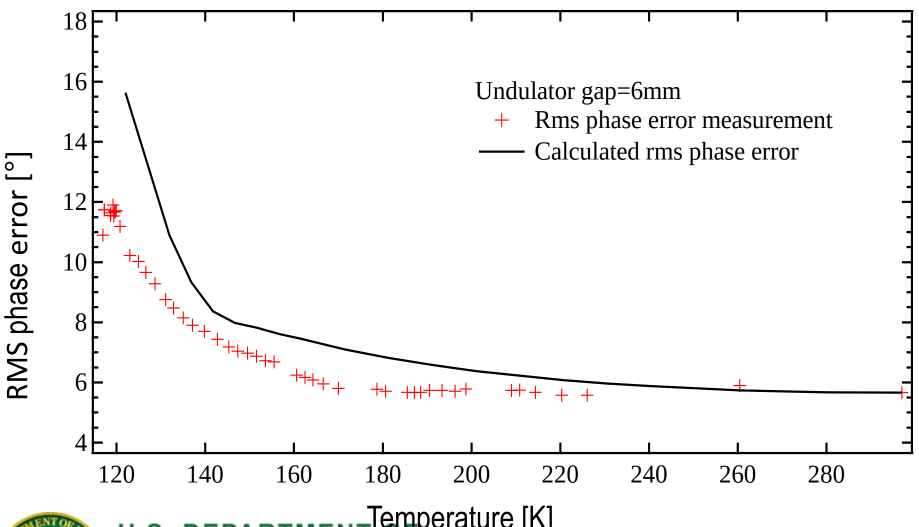



# Local field measurement




Good agreement between measurement and the RADIA model

- Maximum at T=148K
- Small peak field variation <0.5% as the temperature T is between 135K and 180K




RMS phase error

- The RMS phase error increases at low temperature

~ 1° as T > 150K

~ 6° as 120 K < T <150 K

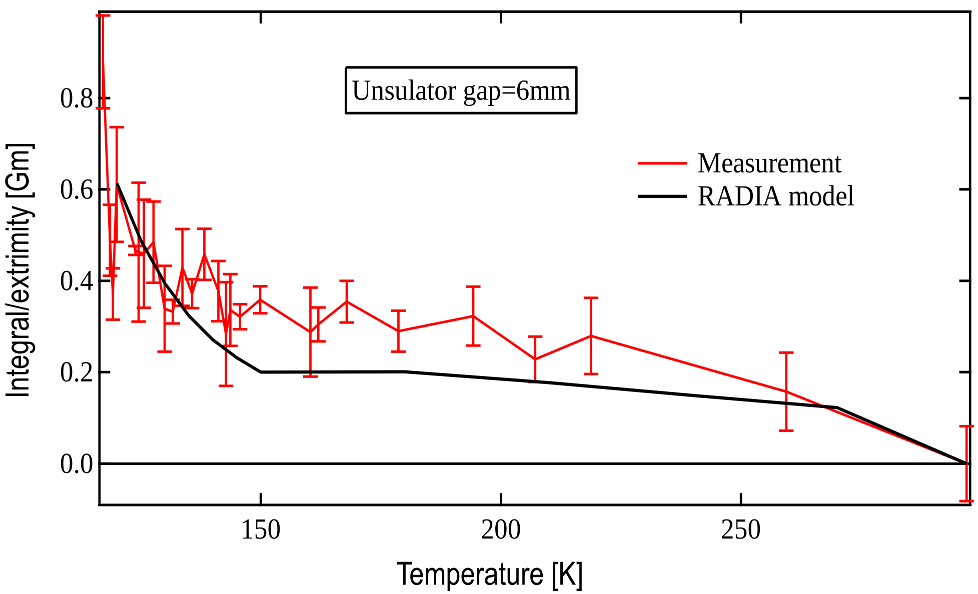
- The longitudinal thermal gradient is responsible for the RMS phase error increase:

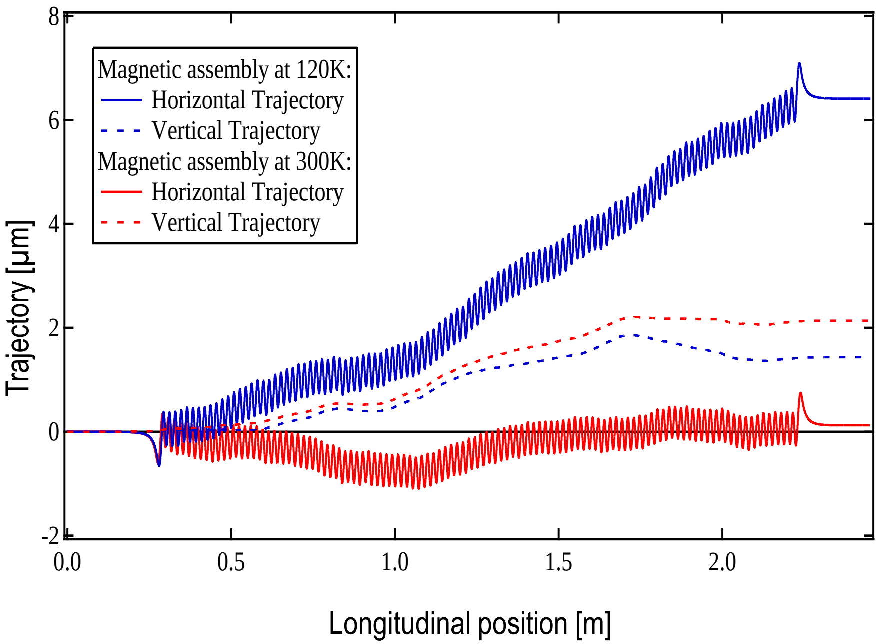
- Gap deformation
- Local change of magnet properties (remanence, permeability)

- The increase of the RMS phase error is acceptable for this device. However a small temperature gradient is necessary to reach a small RMS phase error.

# Field integral

- Good agreement between measurement and the RADIA model which takes into account the change of permeability with temperature
- Extremity effect
- Negligible effect on the horizontal field integral




Field integral variation visible on the trajectory

# Measurement summary

✓Good agreement between RADIA model and the measurement

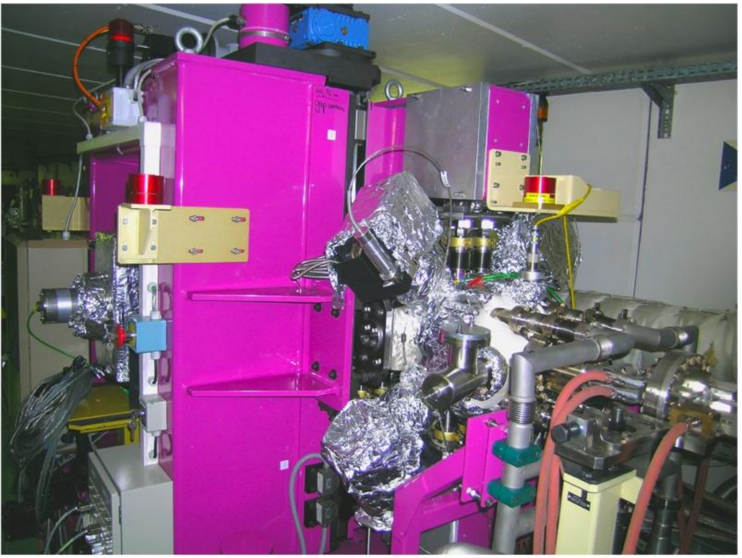
✓Free of local errors

✓Errors linked to the thermal gradient observed along girders
- Longitudinal gradient incompatible with a small RMS phase error <2.5°

✓Improvement still possible:
- Material with higher conductivity
- Include a taper to the technical support in order to compensate for possible thermal gradient

2010-2011: Realization of optimized CPMU
- Small RMS phase error
- High remanence magnet (unbakable ).

# Heat Budget and thermal gradient



| Filling mode | Gap [mm] | Tmag [K] | Extracted power [W] | Power deposited by electron beam [W] |
|---|---|---|---|---|
| 16 Bunch | 30 | 174 | 296 | 87 |
| 16 Bunch | 6.2 | 154 | 252 | 43 |
| 7/8 | 6 | 151 | 241 | 32 |
| 7/8 | 30 | 168 | 280 | 71 |
| Hybrid | 15 | 177 | 315 | 106 |
| No beam | | 138 | 209 | 0 |

Undulator field change ~ 0.3 % according to magnetic measurements
- optimum temperature ~ 150 K at minimum gap

A residual temperature gradient along the magnetic assembly is observed;
- ~ 1 K/m at small gap
- up to 2 K/m at open gap

Courtesy of J. Chavanne
J. Chavanne and Al, SRI-09

# IVU22-6m Specifications for the IXS beamline

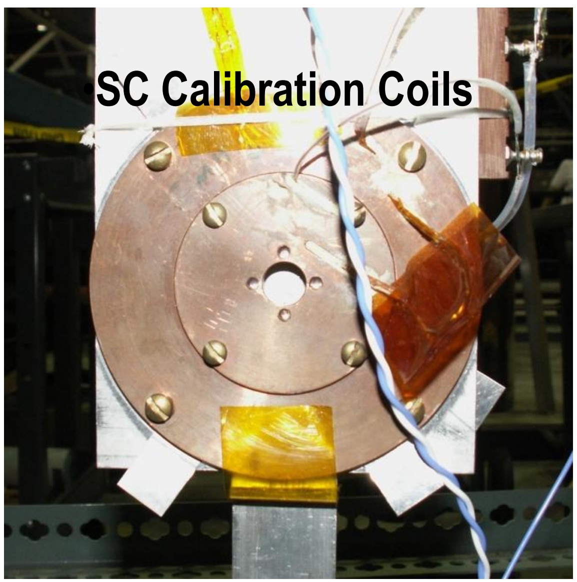
- “Warm Device” assumes NEOMAX-32AH magnet NdFeB with Br = 1.12T
- “Cold Device” assumes NEOMAX-42AH magnet with Br = 1.4T at 120K (T. Tanabe)
- A cold IVU17-5.5m gains 75% more flux than the warm IVU22-6m

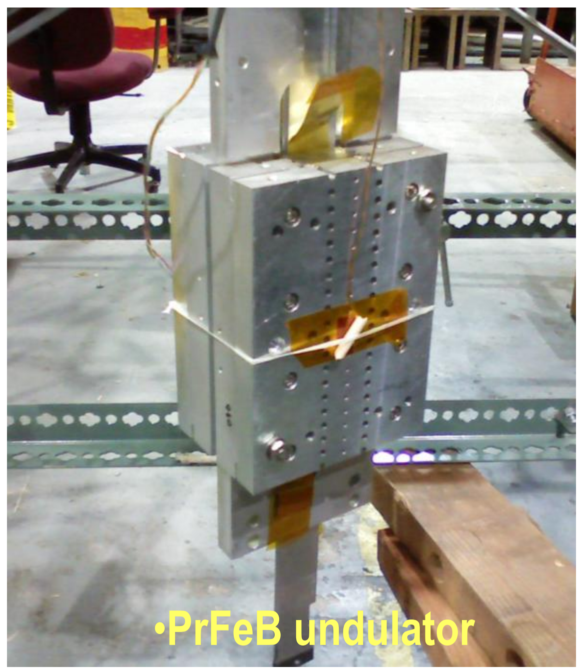
**Courtesy of Yong Cai**

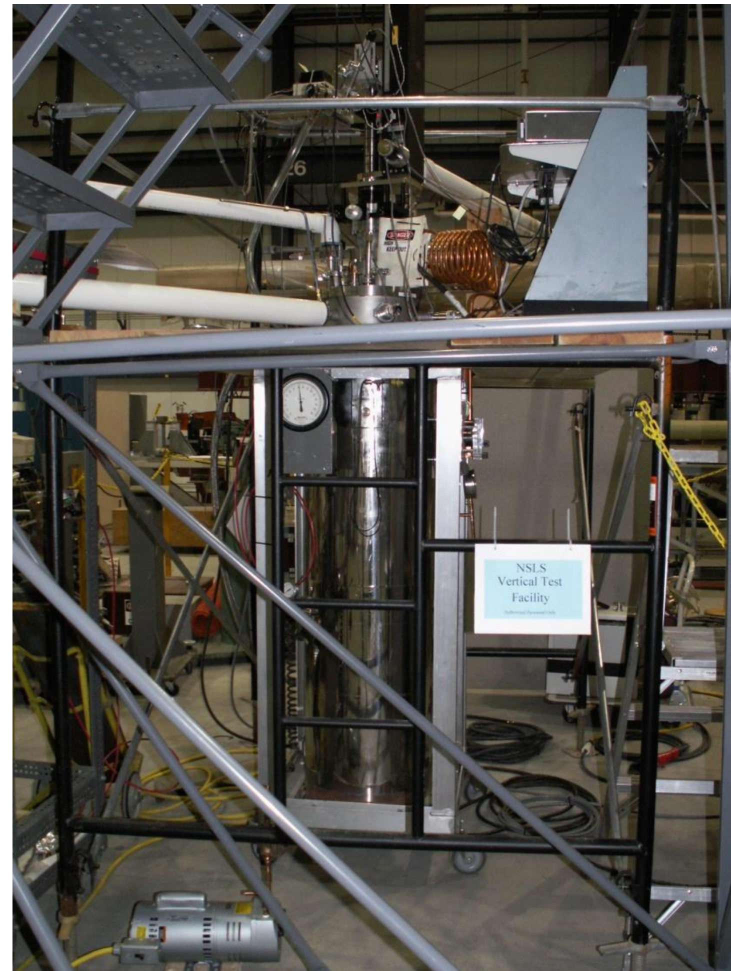
| | Warm Device | | Cold Device |
|---|---|---|---|
| **Undulator Parameters** | #1 (**“Baseline”**) | **#2** | #3 |
| Name | U20-2m | **U22-6m** | U17-5.5m |
| Type | PMU | **PMU** | CPMU |
| Period (mm) | 20 | **22** | 17 |
| Length (m) | 2.14 | **6** | 5.5 |
| No. of Periods | 105 | **270** | 321 |
| Minimum Gap (mm) | 5.4 | **6.9** | 6.7 |
| B Peak Field (T) | 0.97 | **0.81** | 0.74 |
| Keff | 1.81 | **1.52** | 1.17 |
| Harmonic for 9.1keV | 5th | **5th** | **3rd** |
| Total power (kW) | 5.72 | **9.3** | 8.5 |
| **Performance at 9.1keV, 5th harmonic (for 9.3m high-β straight, $\beta_{0x}$=20.8, $\beta_{0y}$=3.4)** | | | |
| Gap value for 9.1keV [mm] | 5.9 | **6.95** | 6.8 |
| K value for 9.1 keV | 1.64 | **1.50** | 1.14 |
| Brightness (phs/sec/mrad$^2$/mm$^2$/0.1%BW) | 1.66E+20 | **3.44E+20** | 5.86E+20 |
| Flux thru 100(H)x50(V) μrad$^2$ (ph/sec/0.1%BW) | 7.78E+14 | **1.55E+15** | 2.71E+15 |
| Total power (kW) | 4.68 | **9.1** | 8.1 |

# Vertical Test Facility (VTF)

- Measured various SCU proto types
- It is also used for PrFeB magnet arrays
- 3 Hall Probes in horizontal direction
- SC Calibration coil for LHe temp. Hall probe calibration

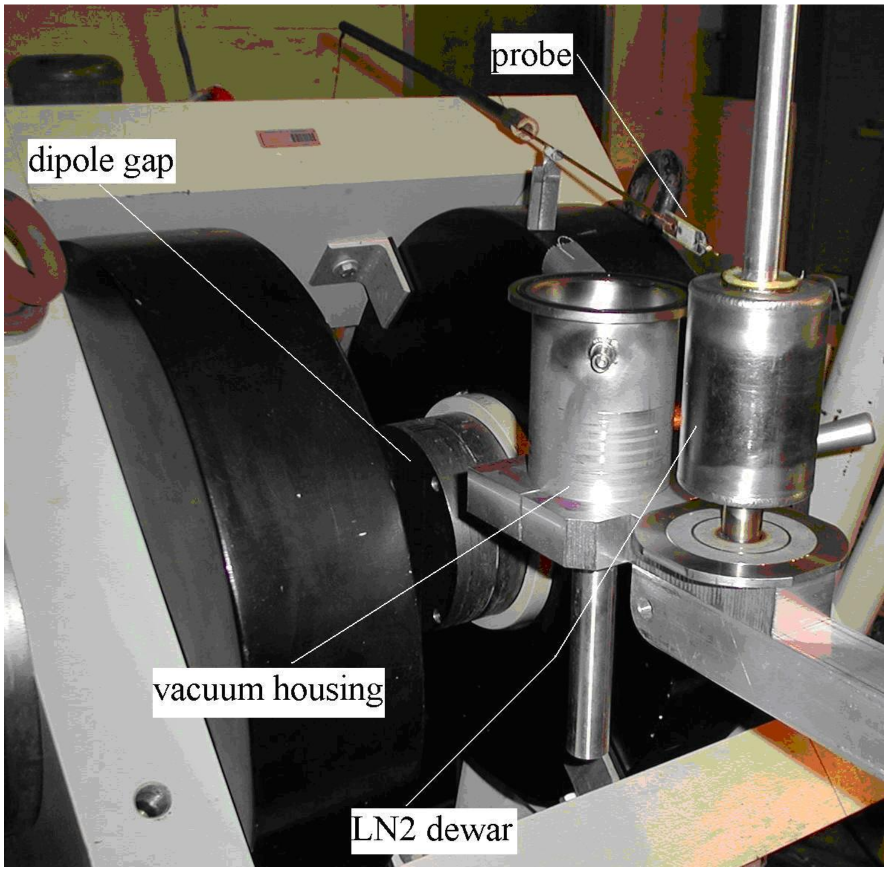


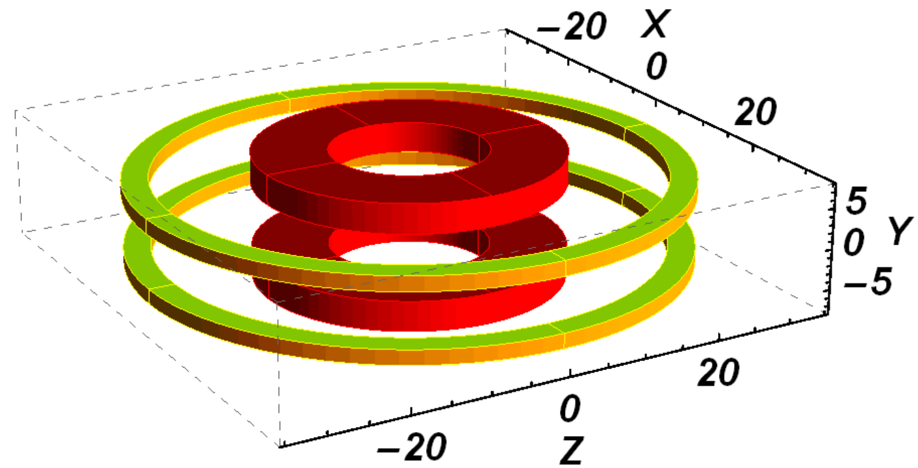



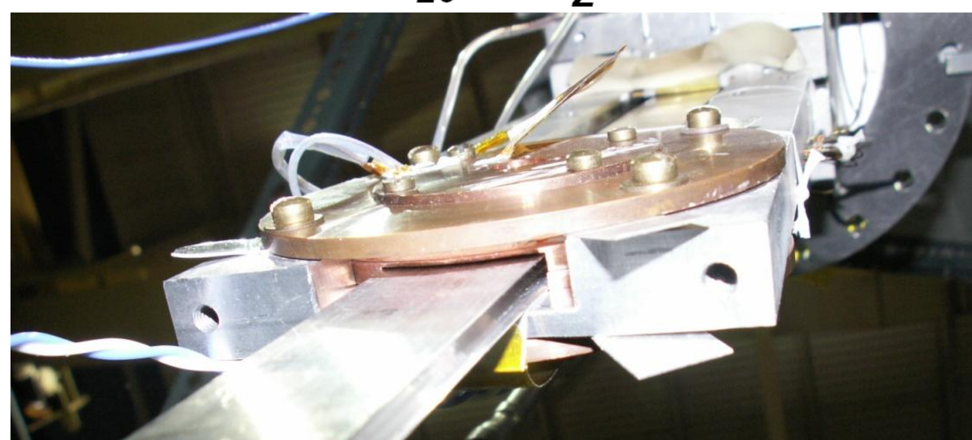



# Low Temperature Hall Probe Calibration

- At 77K, Hall probe is immersed in LN dewar and inserted in calibration dipole
- At 4.2K, SC Dipole coils are used for in-situ probe calibration

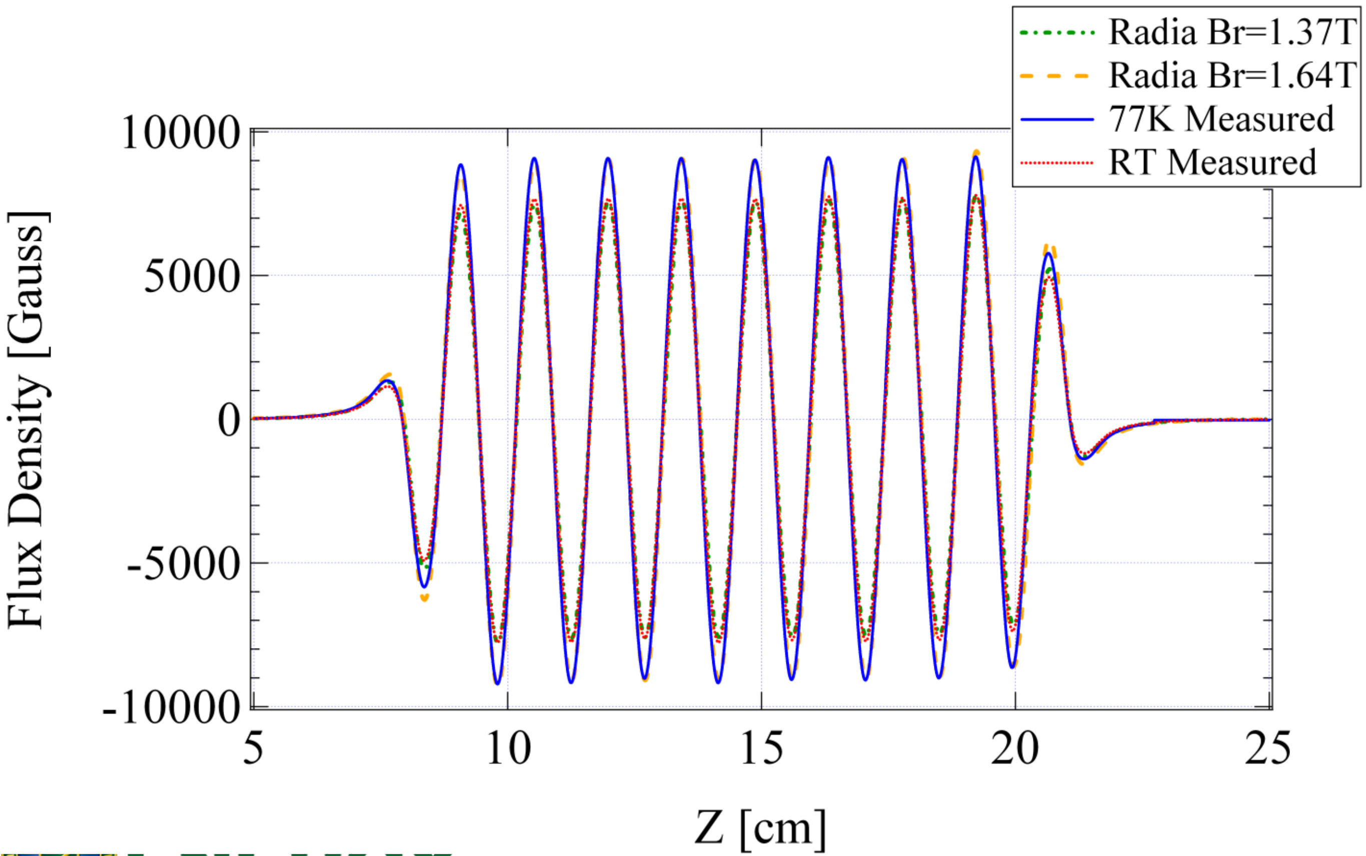


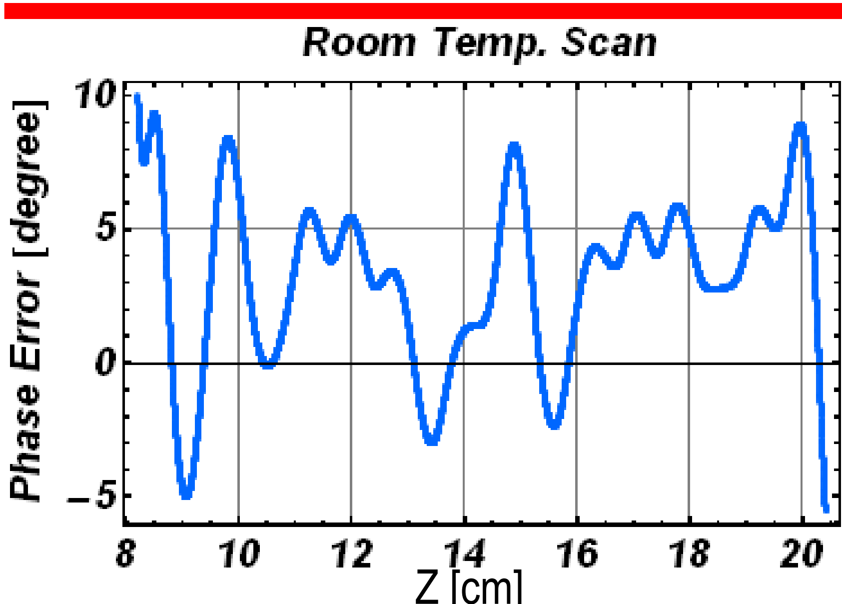
# PrFeB Magnet 77K Measurement

- **PrFeB (53CR v2 magnet) Magnet Arrays**
  - Cut from a large piece → M vector uniformity is poor → Sorted by signature method
  - Period Length = 14.5mm, Gap=4.85mm
  - RT measurement on granite Hall probe bench (Gap=4.85mm) for the reference



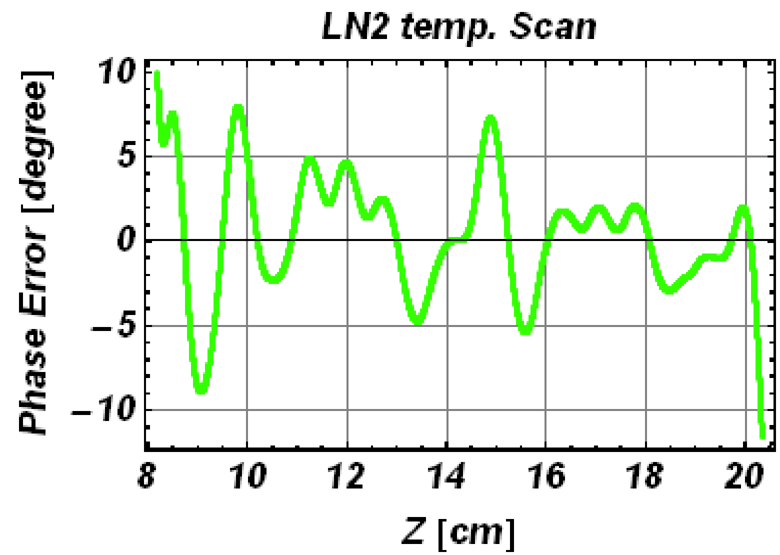

- **Increase of ~19 % in Br**

# Phase Error Change from LN2 to LHe temp.



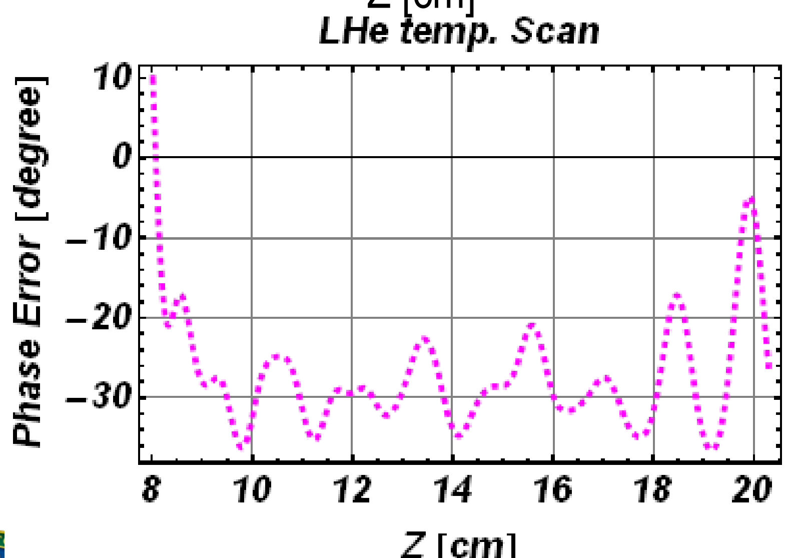

•RMS Phase Error

= 3.1 degree




•RMS Phase Error

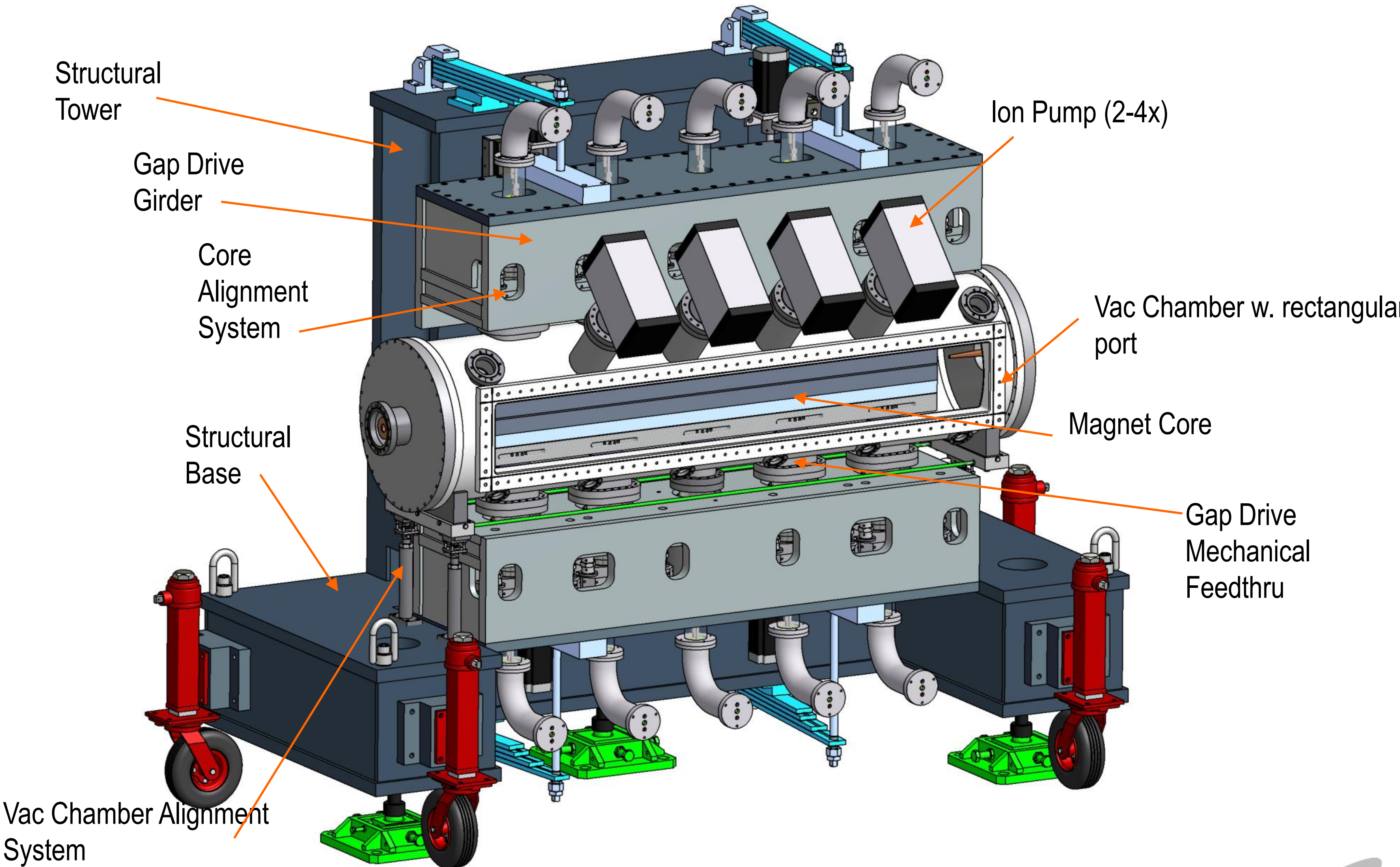
= 3.5 degree




•RMS Phase Error

= 6.8 degree

# NSLS-II IVU/CPMU Mechanical design



# Magnet Array Design Concepts

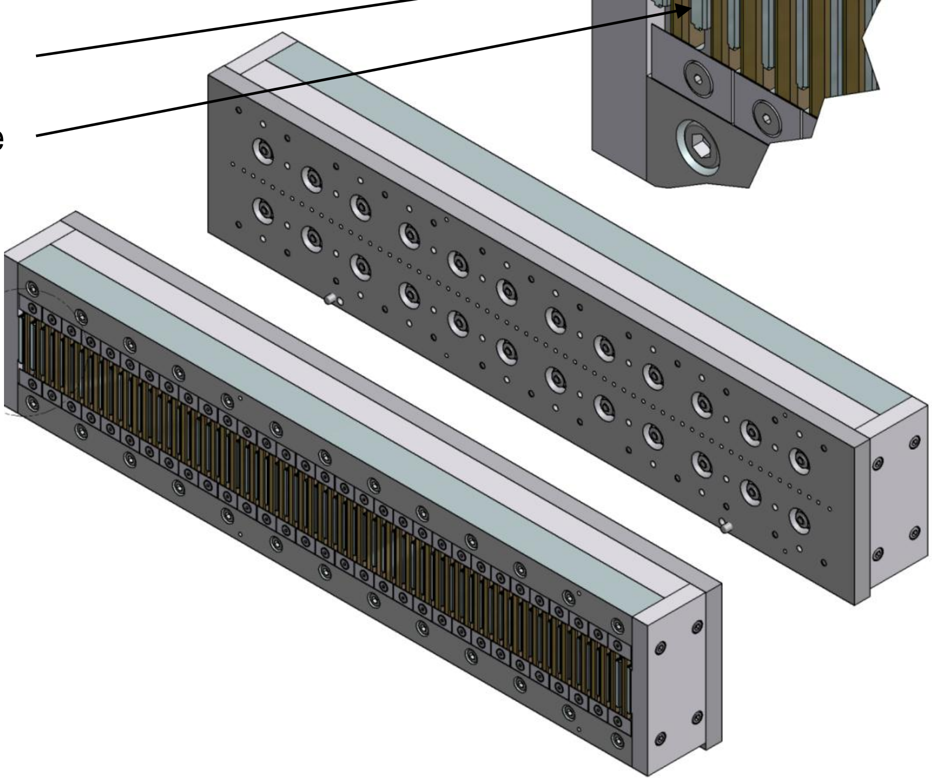
**Machined Rails = repeatable period**

**Base = field flatness**

a) PMP modules

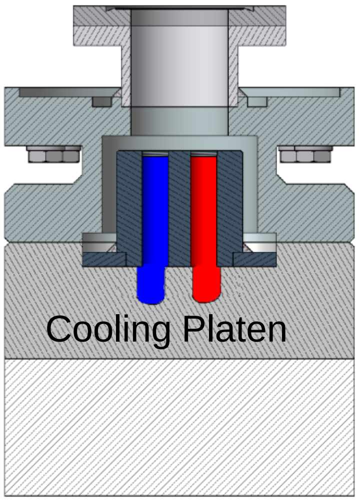

Ti-N plated PM

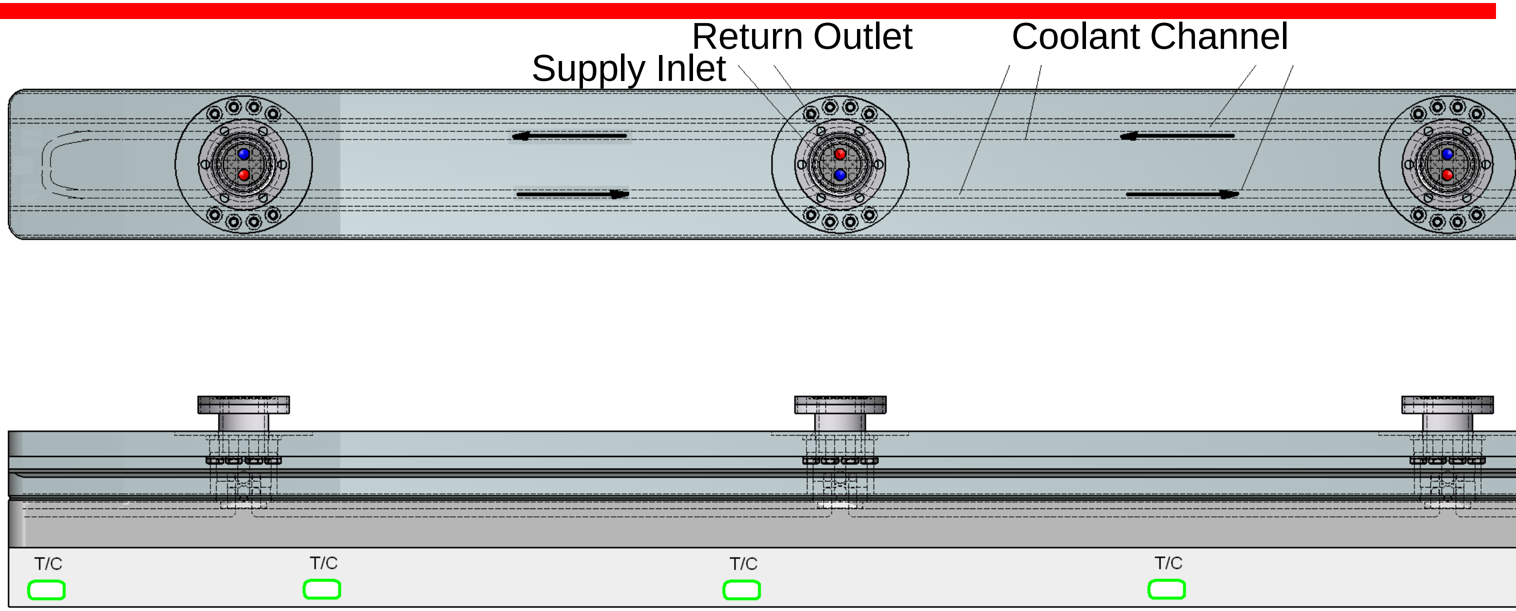
Permendur Pole

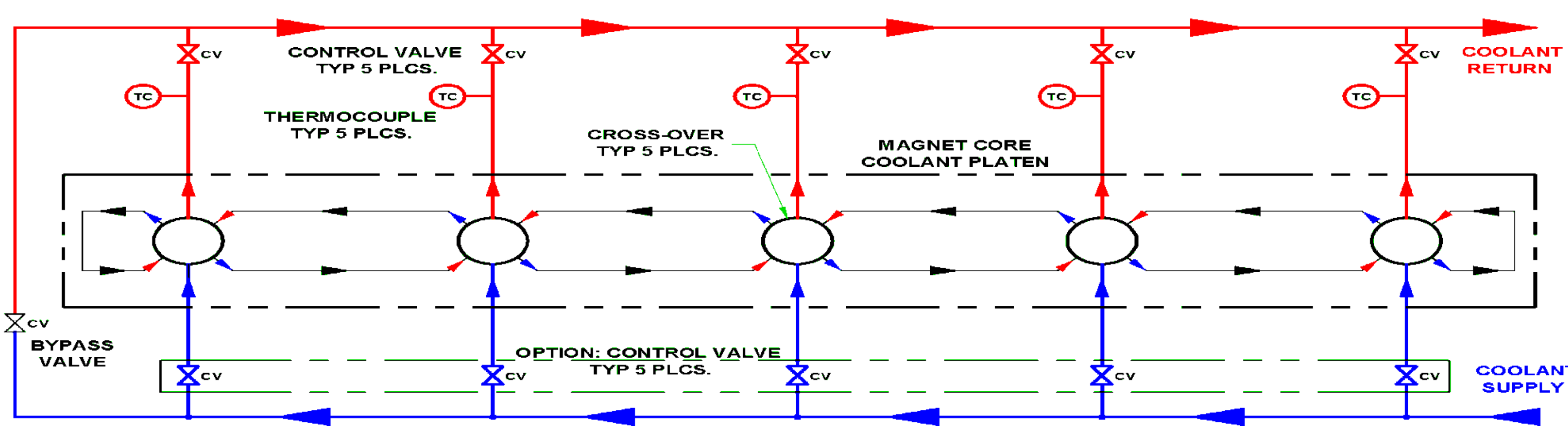


b) segmented arrays ~0.72m arrays

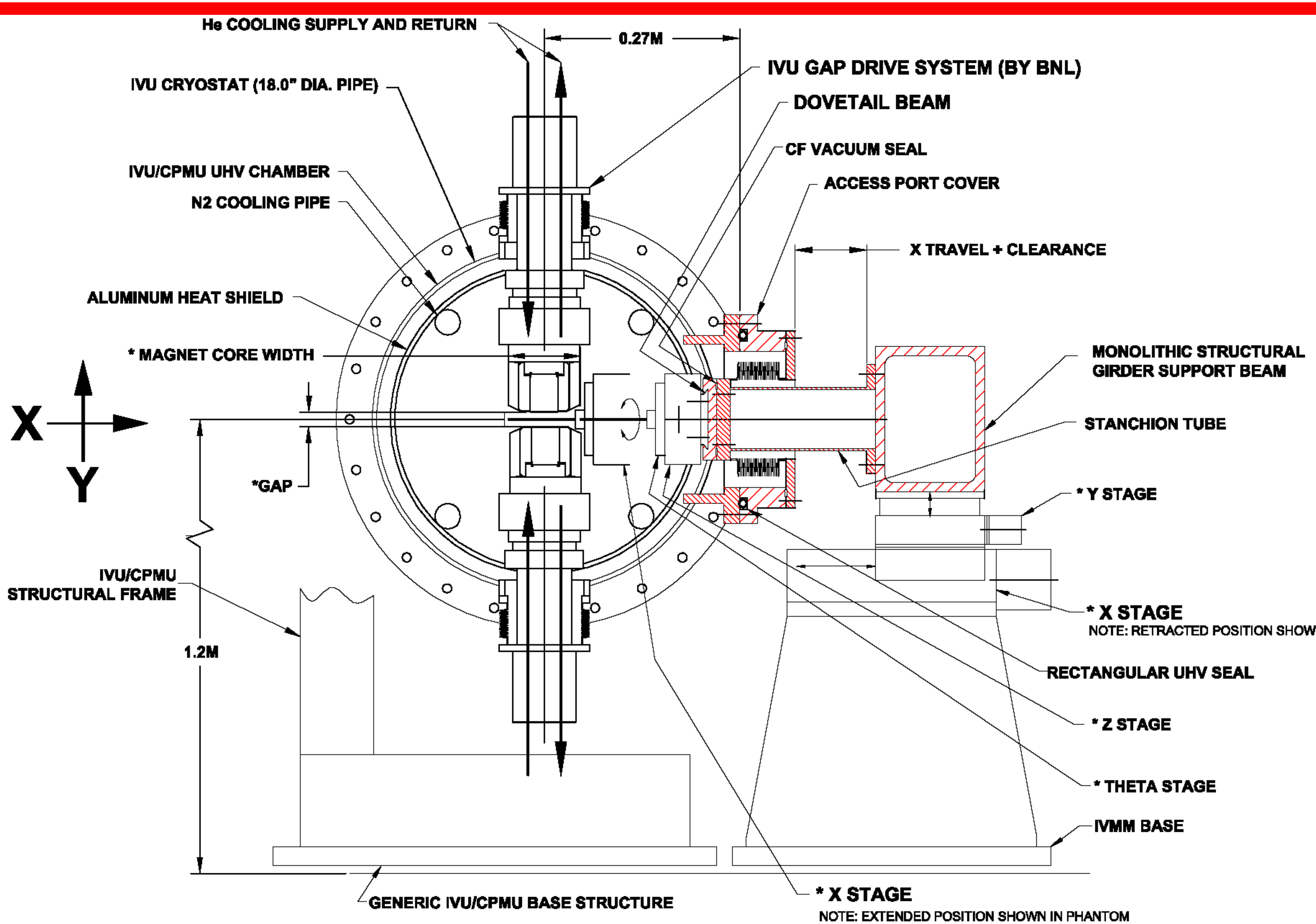
# Magnet Core Assembly and Cross Sections



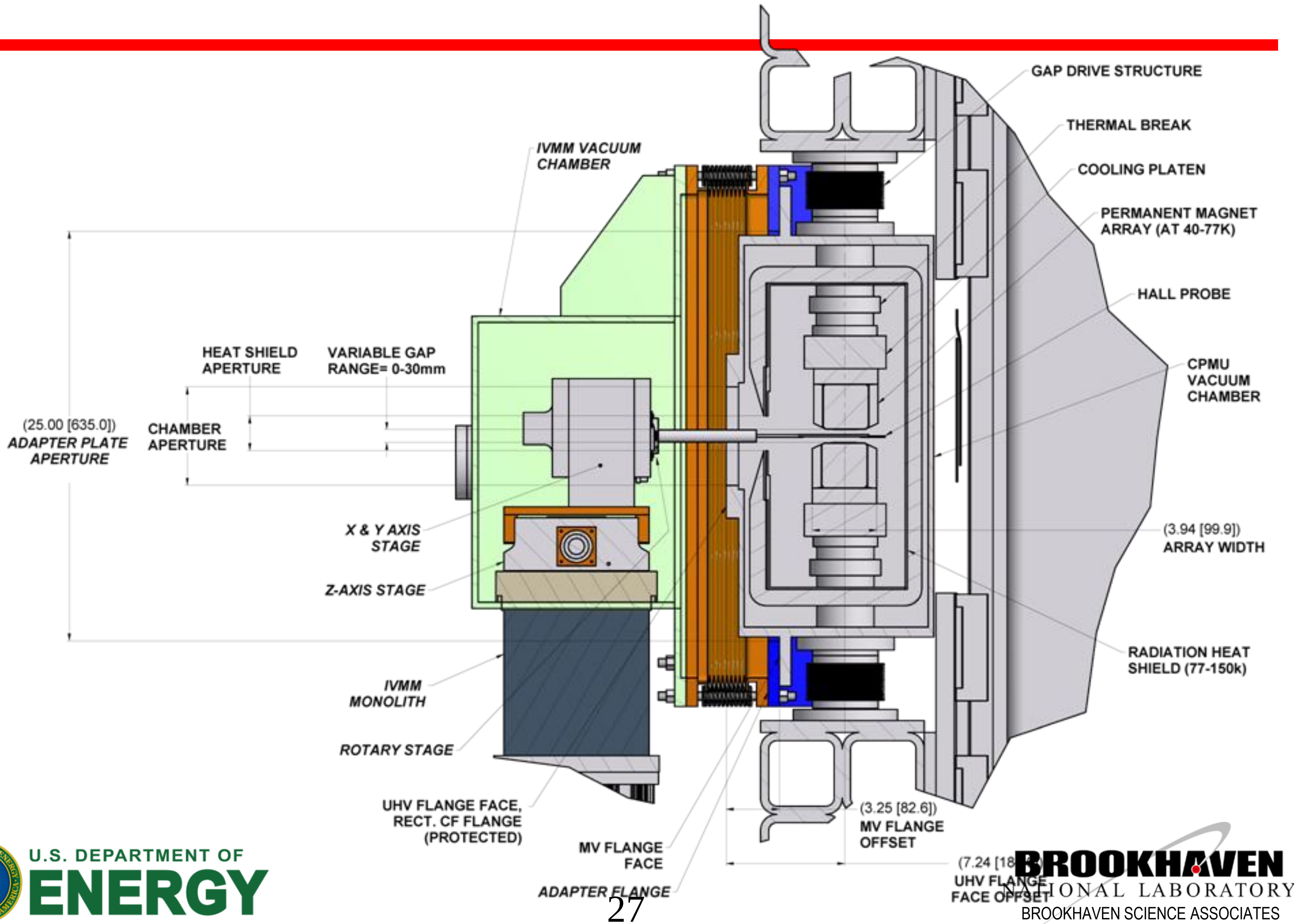



# Modular IVMM concept:  Cross-section



# CPMU on IVMM cross-section: (dwg by W. Wilds)



# Summary

- CPMU successfully installed and tested at the ESRF
- Thermal budget higher than expected
- Several CPMU projects based on $Pr_2Fe_{14}B$ magnet
- At NSLS-II CPMU are alternative to standard IVU (not in the baseline project)