# Field measurement of a cryogenic permanent magnet undulator at TPS

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# Outline

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  - **Spring module and temperature control**
- **Measurement system–**
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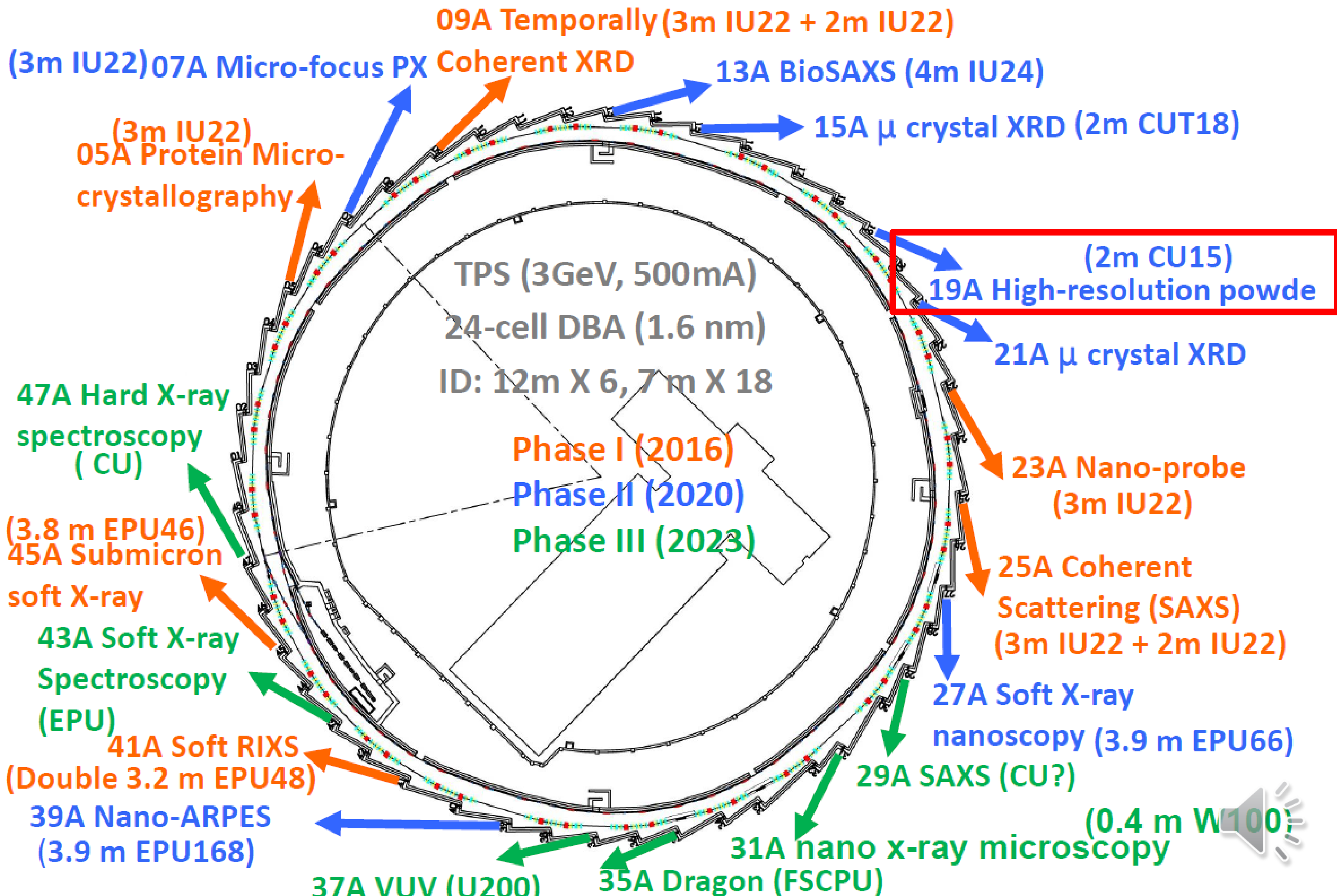
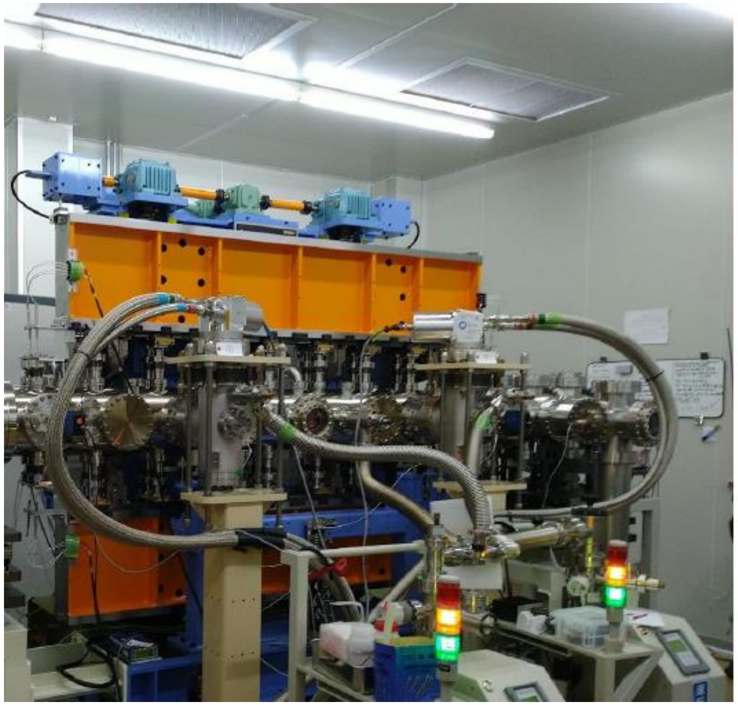
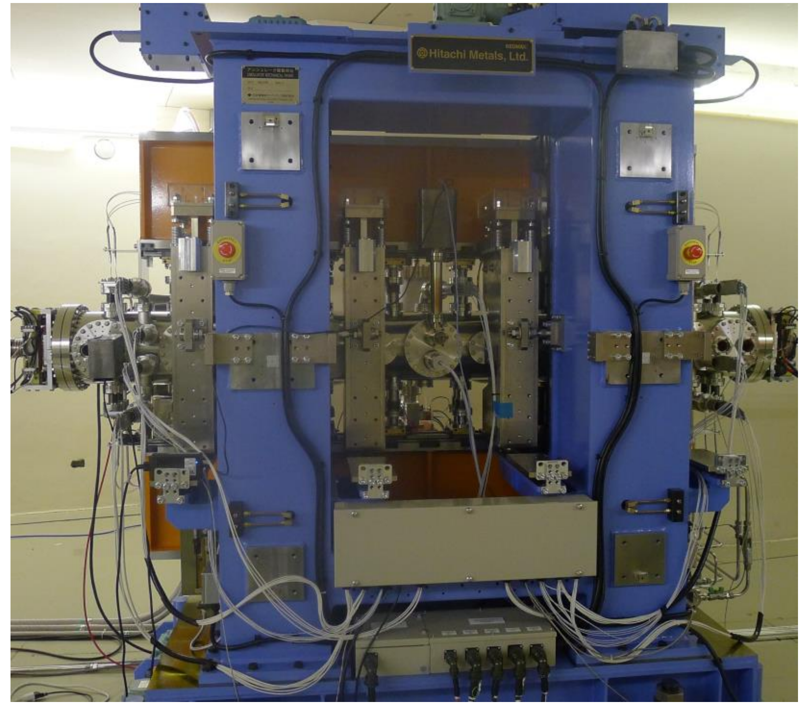
  - **Hall probe calibration**
- **Field tuning**
  - **Differential adjusters**
  - **Spring modules**
- **Summary**

# CPMUs of the TPS



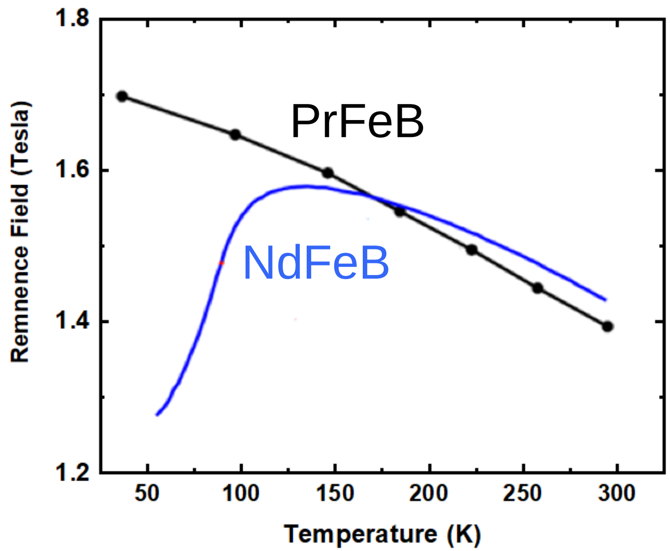
# CPMU15

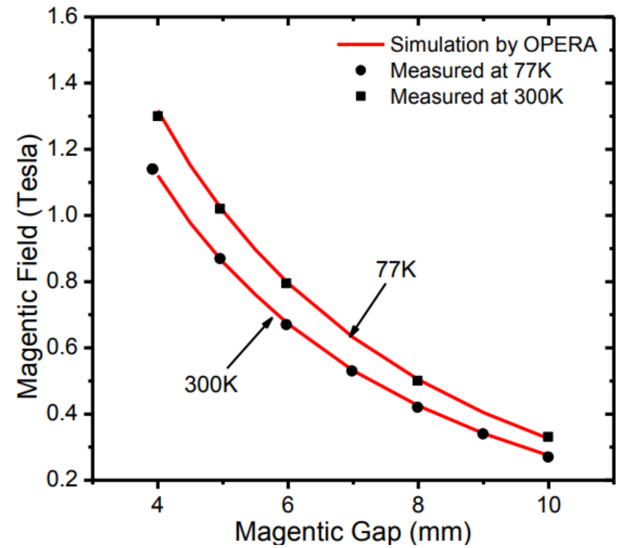





| Items | unit | Cryogenic Temperature | Room Temperature |
|---|---|---|---|
| Magnet material | | $Pr_2Fe_{14}B$ (NMX-68CU) | |
| Period | mm | 15 | |
| Min. magnetic gap ($G_{mag}$) | mm | 4.00 | |
| Effective magnetic field | Tesla | 1.30 | 1.13 |
| Deflection parameter | | 1.81 | 1.58 |
| Magnetic force | kN | 31.8 | 23.0 |
| Number of periods | | 133 | |
| Total cooler capacity | Watt | 400 | |
| Operating temperature | K | 80 | 300 |

# Magnet material



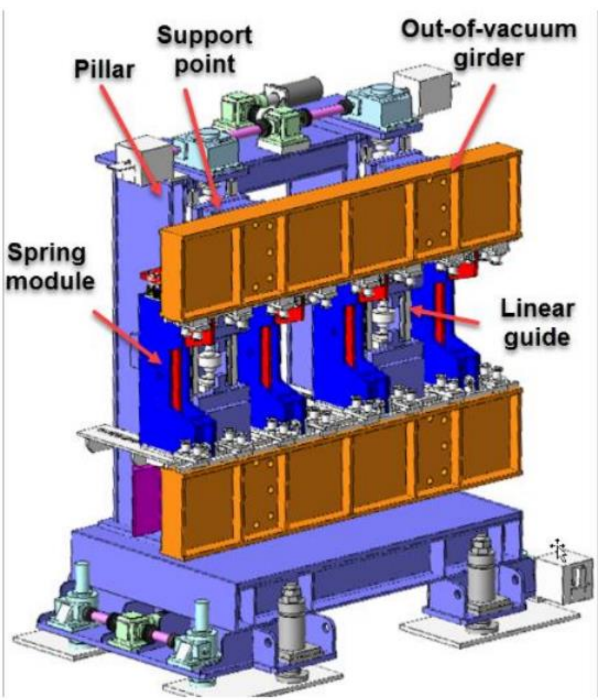

| Items | Unit | Value |
|---|---|---|
| Magnet structure | | Hybrid |
| Magnet material | | $Pr_2Fe_{14}B$<br>NMX-68CU |
| Remanence ( *Br* ) | T | 1.4 at 293 K<br>1.67 at 77 K |
| Coercivity ( *Hcj* ) | kA/m | 1689 at 295 K<br>6200 at 77 K |
| Magnet size (x,y,z) | $mm^3$ | 2.25 × 56 × 20 |
| Pole material | | Vanadium<br>Permendur |

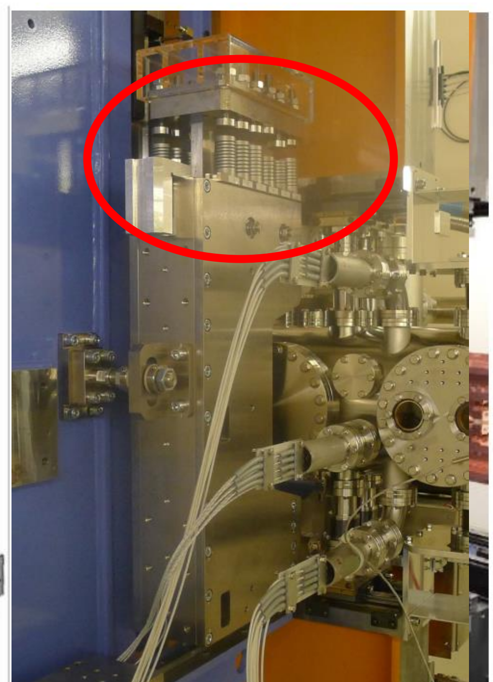

T. Hara and et al, Phys. Rev. ST ACCEL. Beams. 7, 050702 (2004)

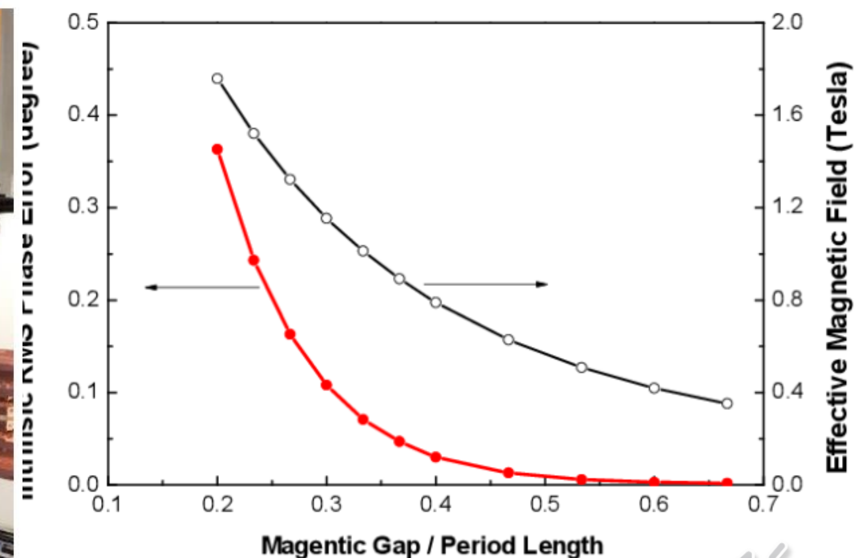
J. C. Huang et al., "Development of cryogenic permanent magnet undulators at NSRRC", *Proc. AIP Conf.*, vol. 2054, no. 1, 2019.

# SPRING COMPENSATING MODULES

- Increased magnetic forces lead to intrinsic phase error.
- Additional four spring module configuration can reduce the intrinsic phase error.
- Not only to compensate magnetic forces but also to obtain a mostly stress free mechanical frame.
- Set-up in air, installed between upper and lower out of vacuum girder.
- Machined-springs to provide good reproducibility

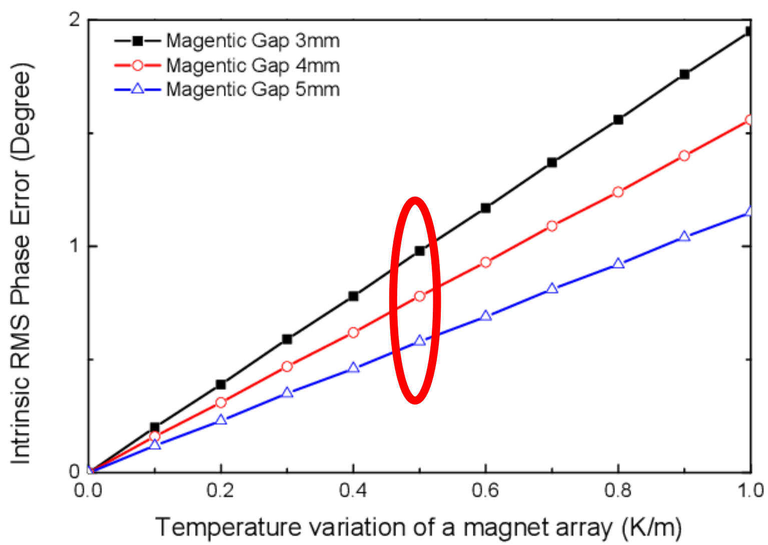


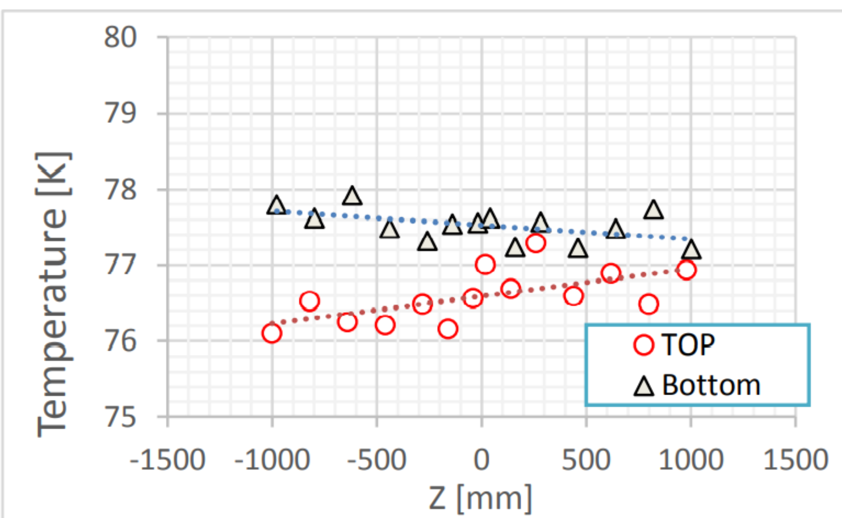


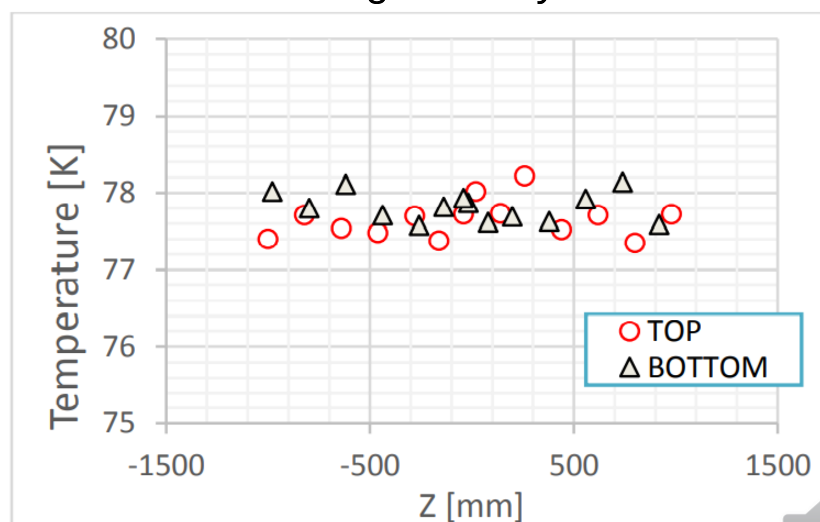

J. C. Huang et al., "Development of cryogenic permanent magnet undulators at NSRRC", *Proc. AIP Conf.*, vol. 2054, no. 1, 2019.

# Temperature control




- A temperature gradient along the magnet arrays causes a gap tapering and changes in the magnet performance.
- The temperature gradient should be controlled to within 0.5 K/m to keep the intrinsic phase error less than 1 degree.
- Temperatures are monitored by 32 calibrated resistance temperature detectors (RTDs) with a tolerance of 0.1K.
- The temperature is about 80 K and the temperature variation is controlled within 0.5 K in a 2-m magnet array.



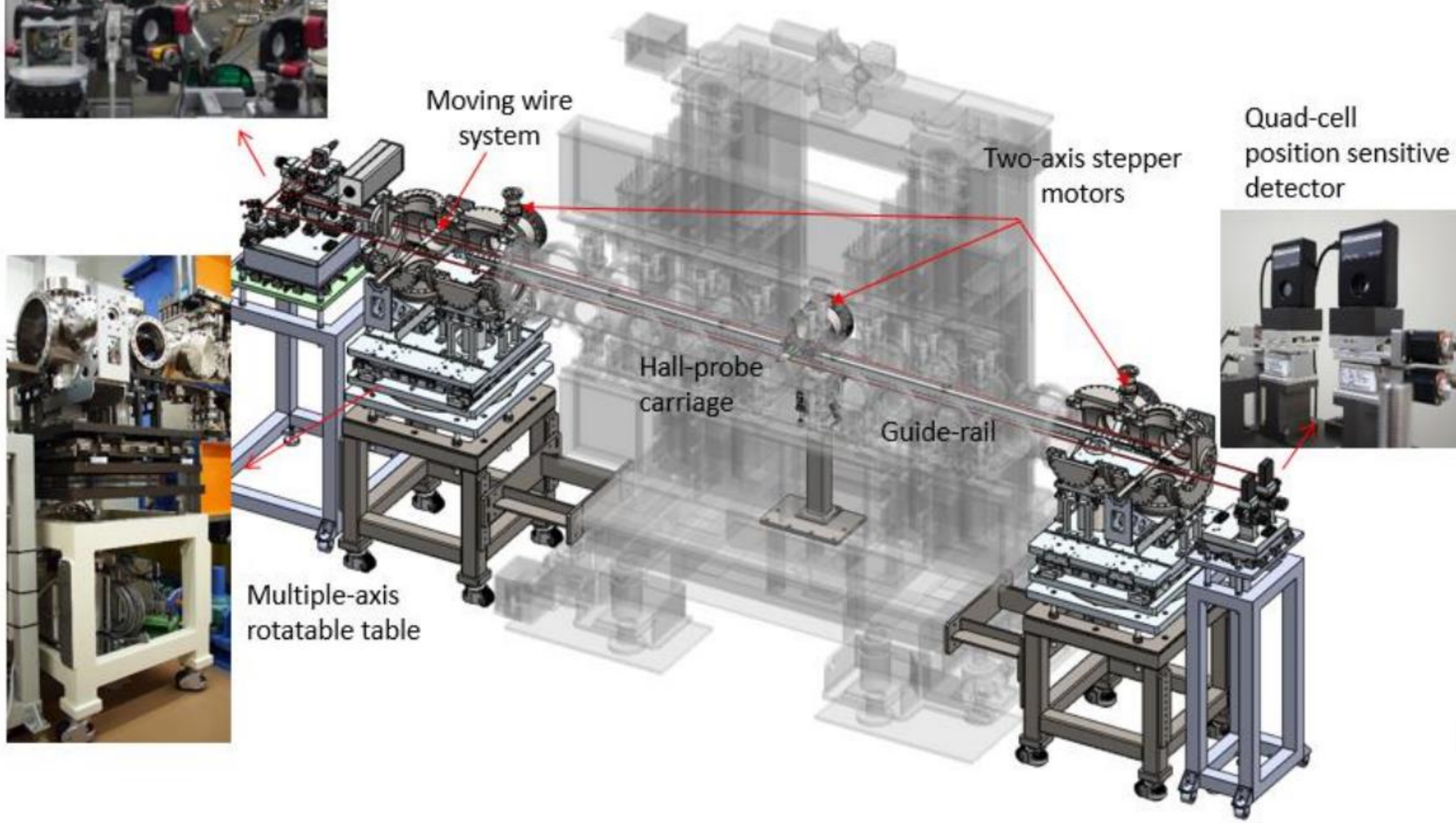




J. Huang, et al., Development of a cryogenic permanent magnet undulator for the TPS, in: Proceedings of IPAC, Copenhagen, Denmark, 2017, pp. 1562–1565.

# Field measurement system

REPRODUCIBILITY OF THE MEASUREMENT SYSTEM

| | XY POSITION VARIATIONS (μm) | Field variations at 1T (%) | Phase error (degree) |
|---|---|---|---|
| Cryocooler off | $<\pm10$ | $< 0.01$ | $\pm 0.2$ |
| Cryocooler on | $<\pm12$ | $< 0.015$ | $\pm 0.3$ |

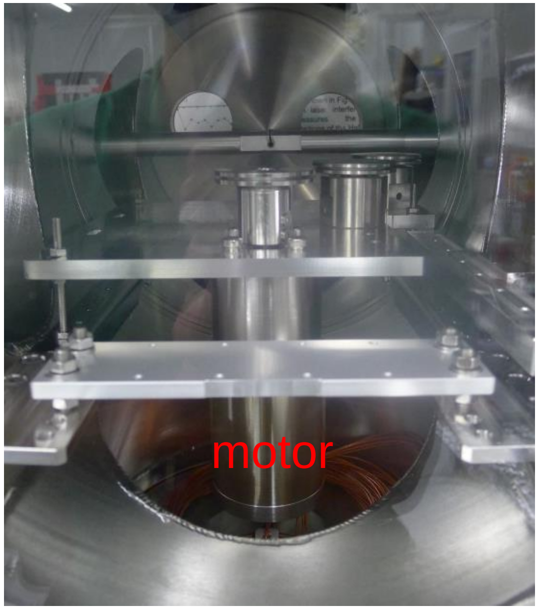



# Measurement system upgrades

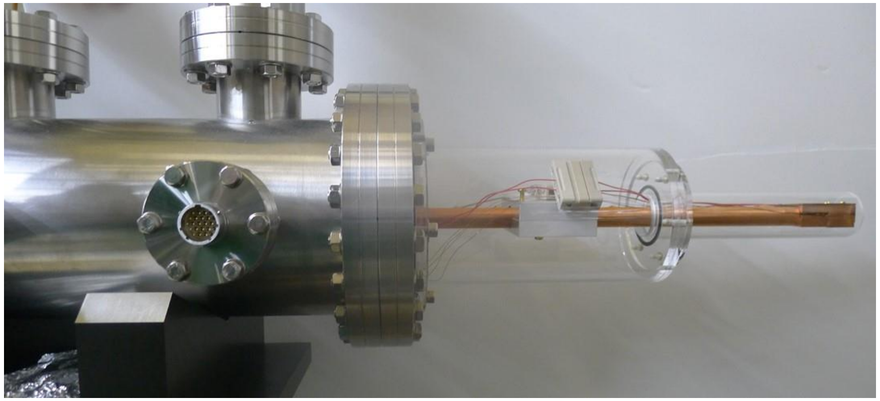
Further modifications to enhance its durability and simplify its alignment capabilities

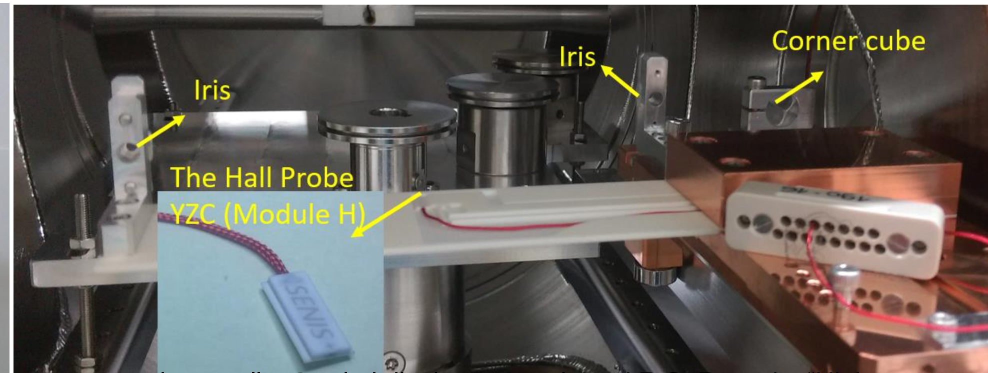
- Replace the laser to get uniform profile
- Higher loading stages to avoid missing steps
- In vacuum motor to reduce vibrations
- Thicker signal wire to avoid broken






# Hall probe calibrations

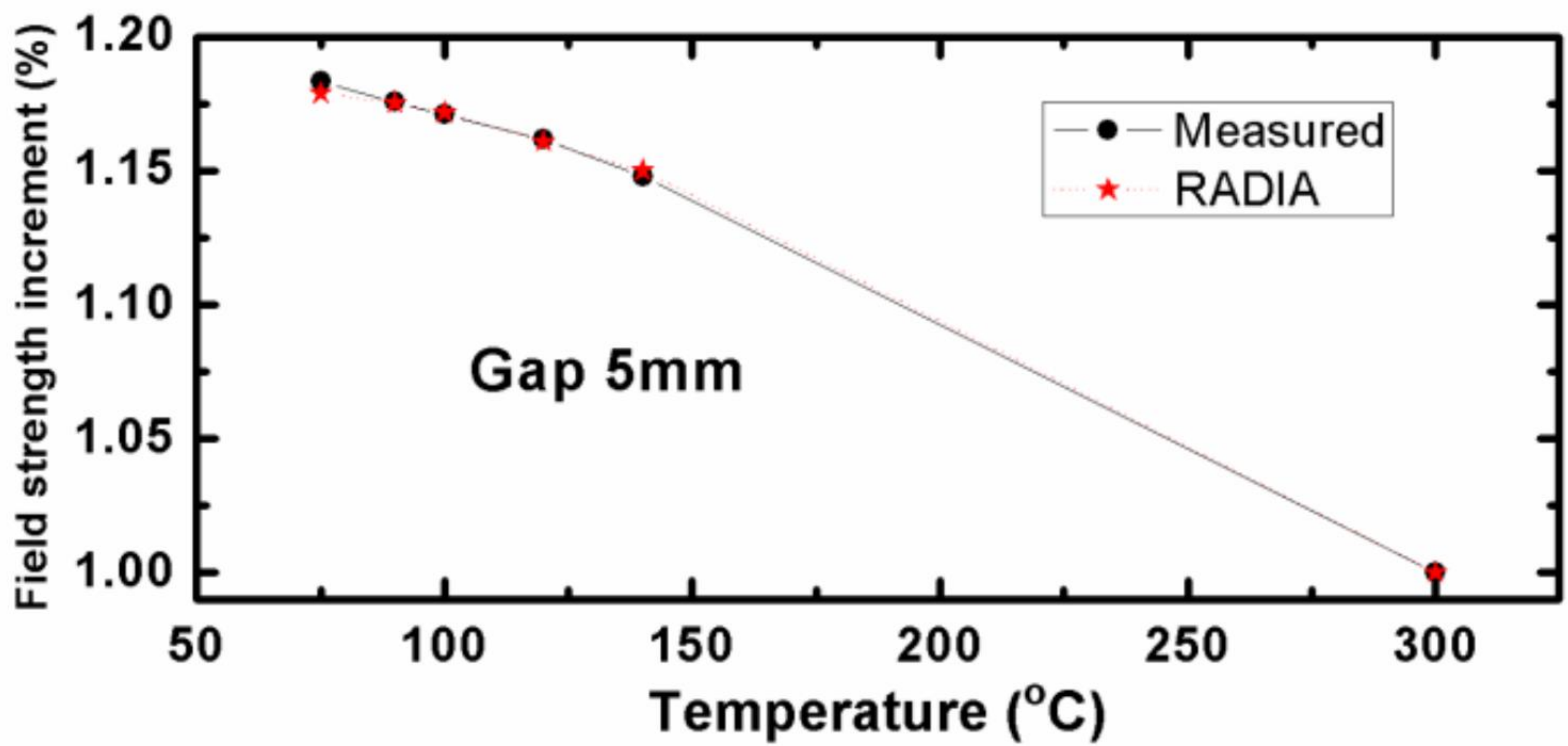





D. Popovic Renella, S. Dimitrijevic, S. Spasic and R.S. Popovic, "High - accuracy teslameter with thin three -axis Hall probe", Measurement, vol. 98, 407 (2017).

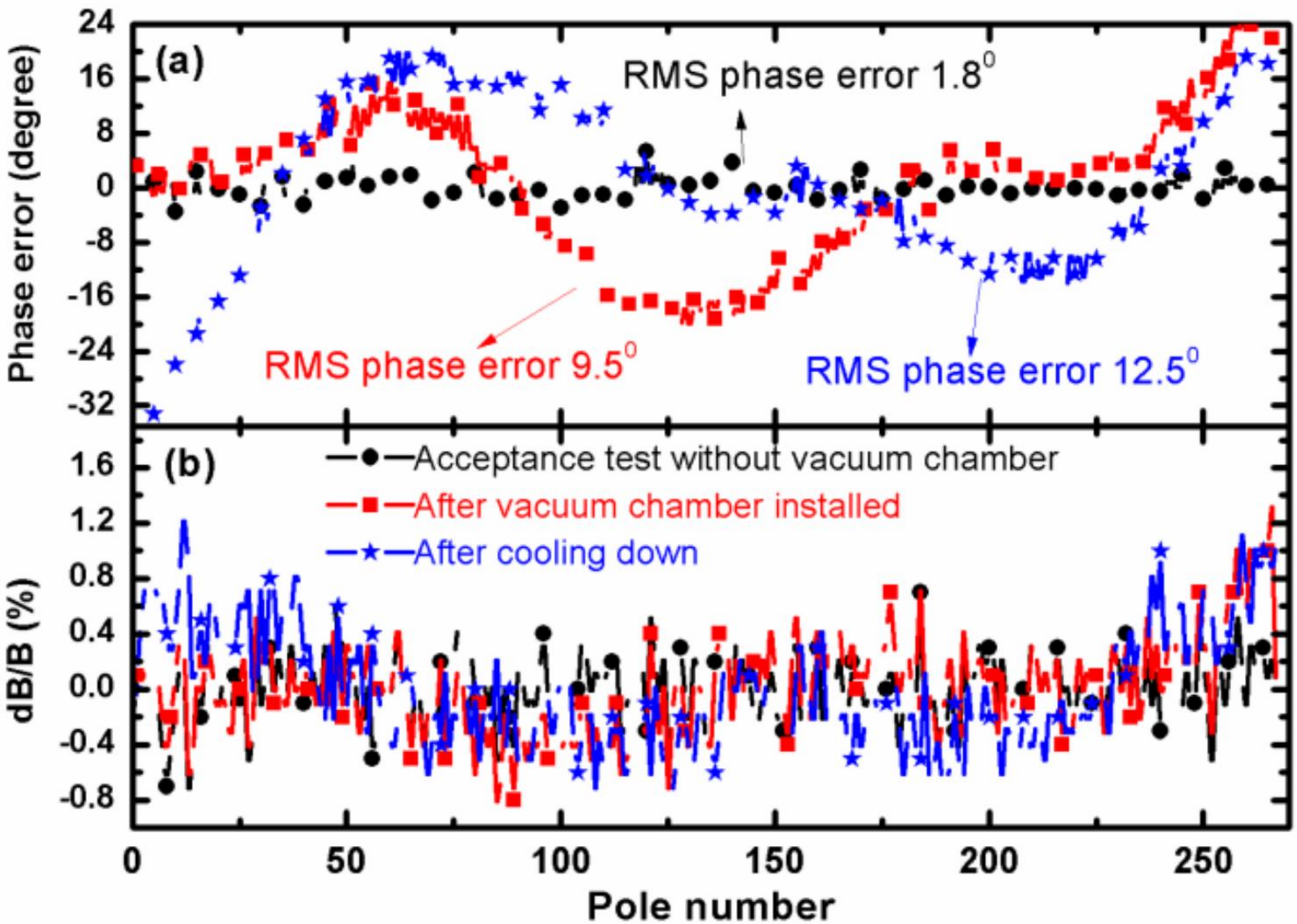

- SENIS YZC (module H) Hall probe
- METRO-lab precision NMR tesla meter (PT2025)
- Cryo-cooler to change the temperature of the Hall probe.
- Motorized stages to change NMR probes

# Field strength of different temperature




- Temperatures are measured by 32 thermometers.
- Supporting rods contract compensated by monitoring two high resolution LED micrometers.
- The magnetic field was found to be larger by 18 % at 77 K compared to room temperature, which is very close to the prediction by the RADIA code

# Field performance




- RMS phase error degrades after the vacuum chamber is installed.
- After cool down, the RMS phase error gets even worse.
- Field variations of some poles are larger than 0.3 % after vacuum chamber installed.

# Field error sources

The peak field can be numerically fitted as a function of the magnet parameters

$$B_0(g) = b_0 \exp\left[b_1 \times g/\lambda_u + b_2 (g/\lambda_u)^2\right]$$

Field errors from magnetic gap variations

$$\Delta B/B = A \times \Delta g/\lambda_u \,, \quad A = b_1 + 2b_2 \times \Delta g/\lambda_u$$

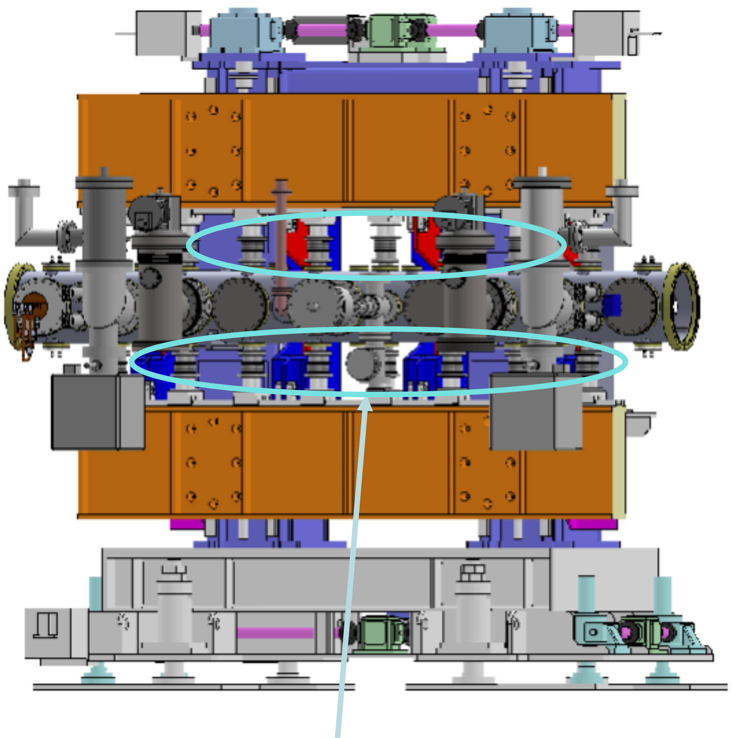
Field errors from Hall probe position errors

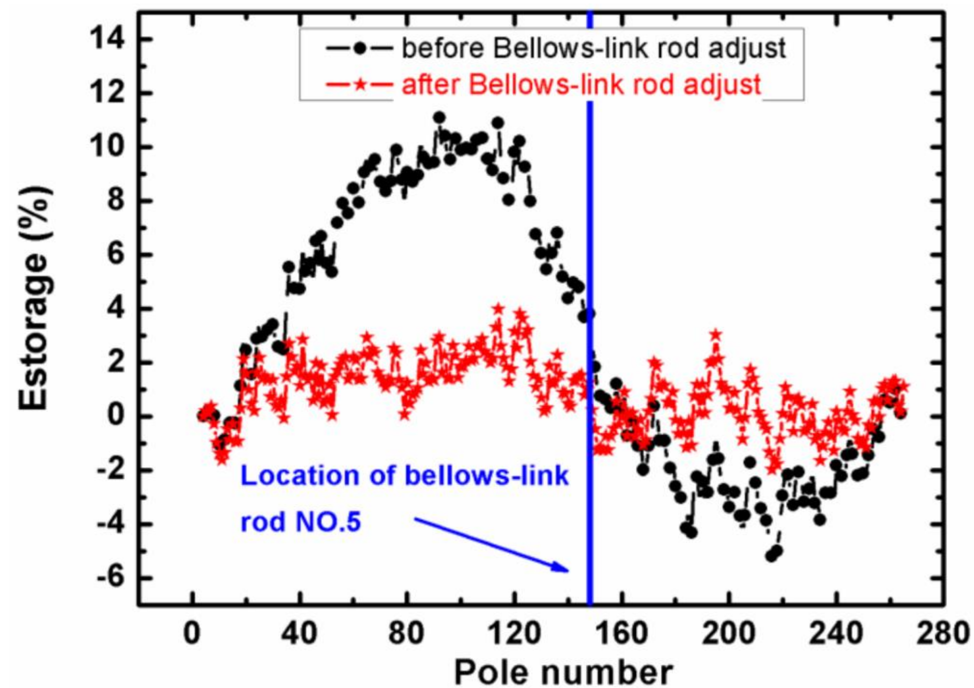
$$\Delta B/B = \left(4b_2 + 2A^2\right)(\Delta y/\lambda_u)^2$$

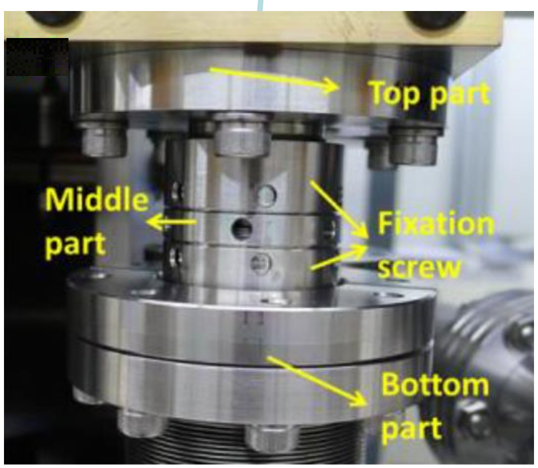
Computational results of field errors

| ΔB/B=0.1% | | |
|---|---|---|
| Gap (mm) | Δy(μm) | Δg(μm) |
| 5 | 53.1 | 2.3 |
| 12 | 40.2 | 1.8 |
| ΔB/B=0.3% | | |
| 5 | 91.9 | 6.7 |
| 12 | 69.7 | 5.3 |

# Field tuning – differential adjusters

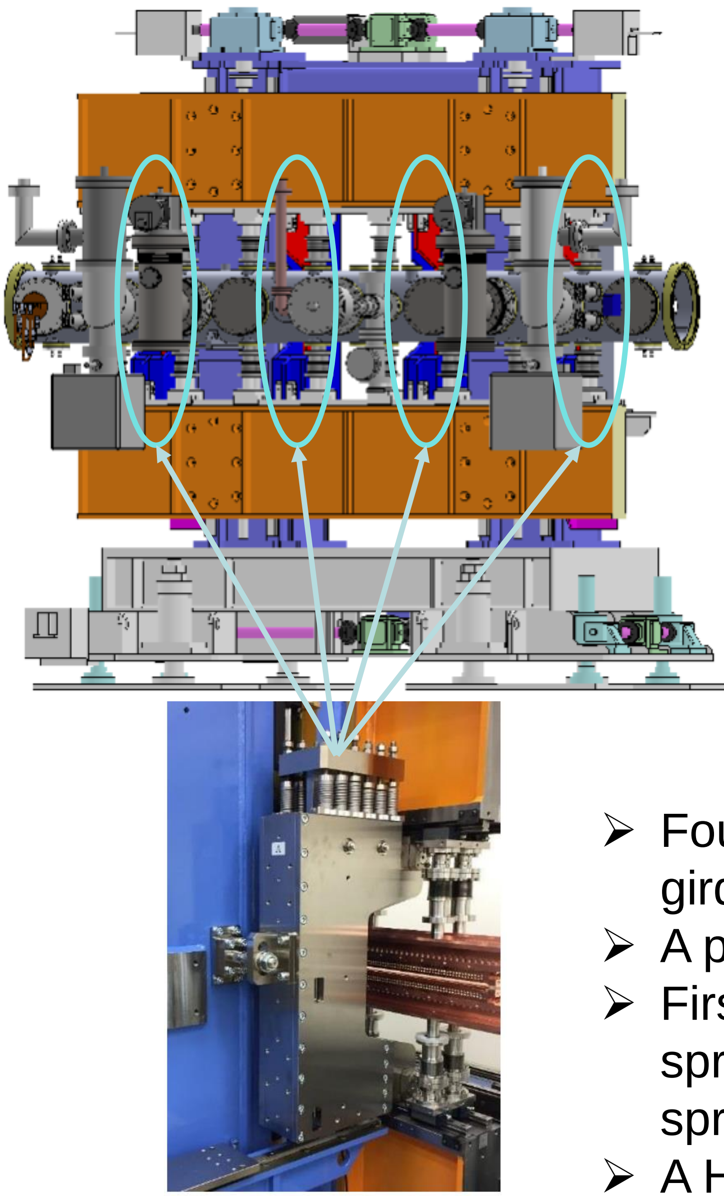


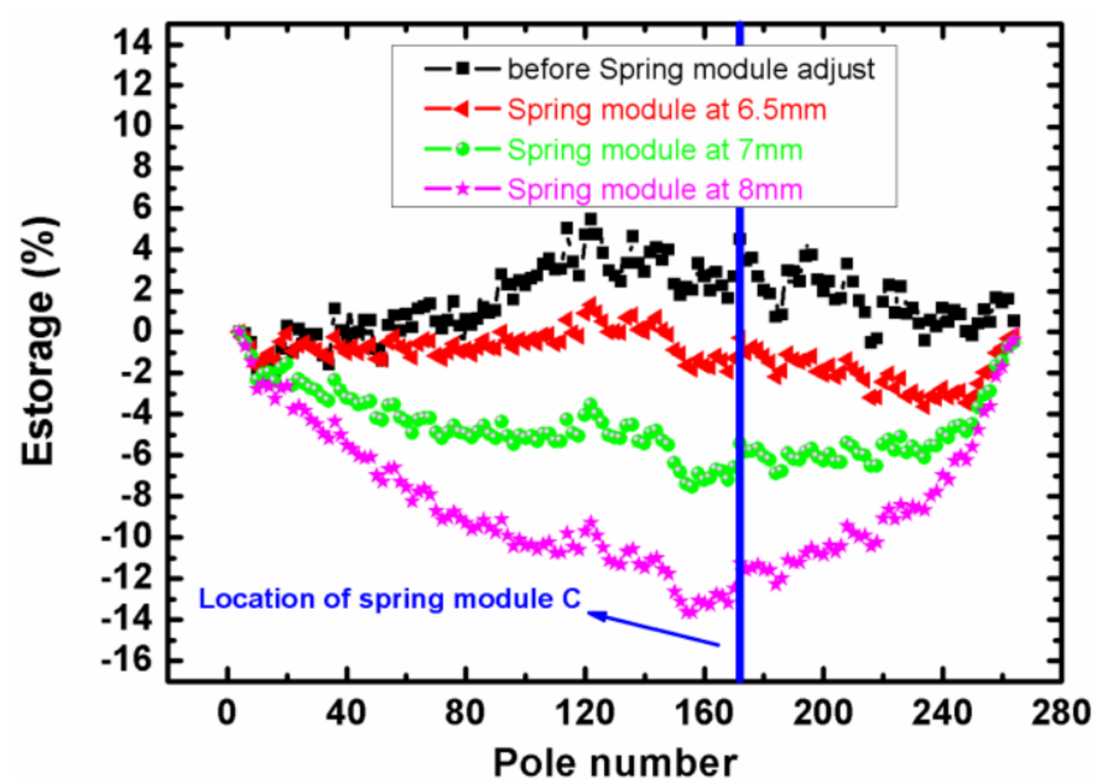



- Thirty two differential adjusters.
- Change length with a resolution better than 1 μm.
- A program predict the amount of adjustments
- First tune at a gap of 12 mm then close gap. (force free)
- A Hall probe reads the field strength during tuning.

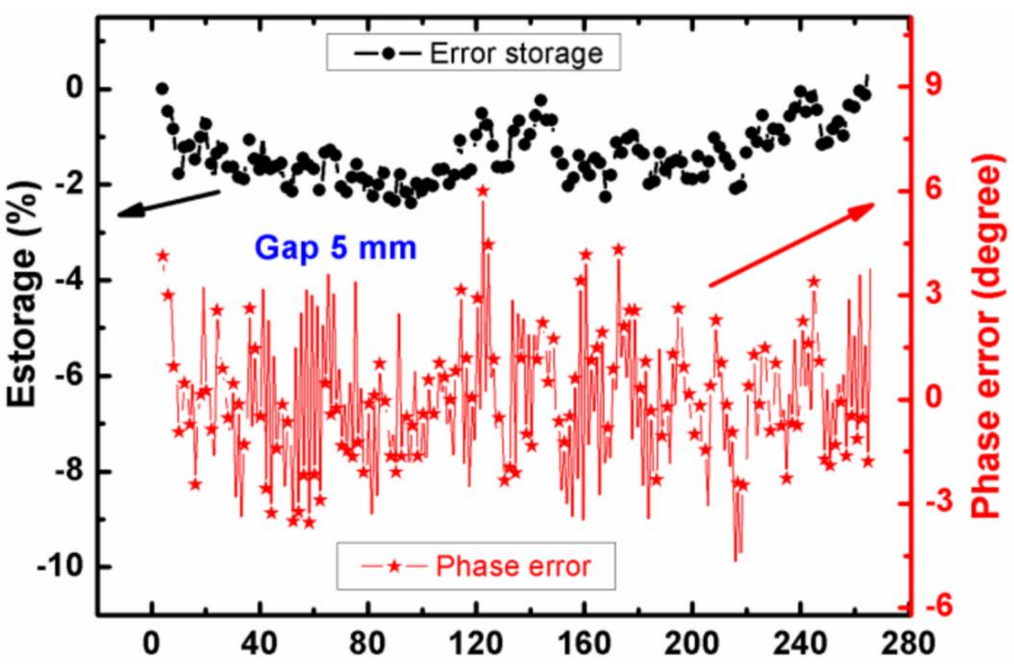
# Field tuning – spring modules

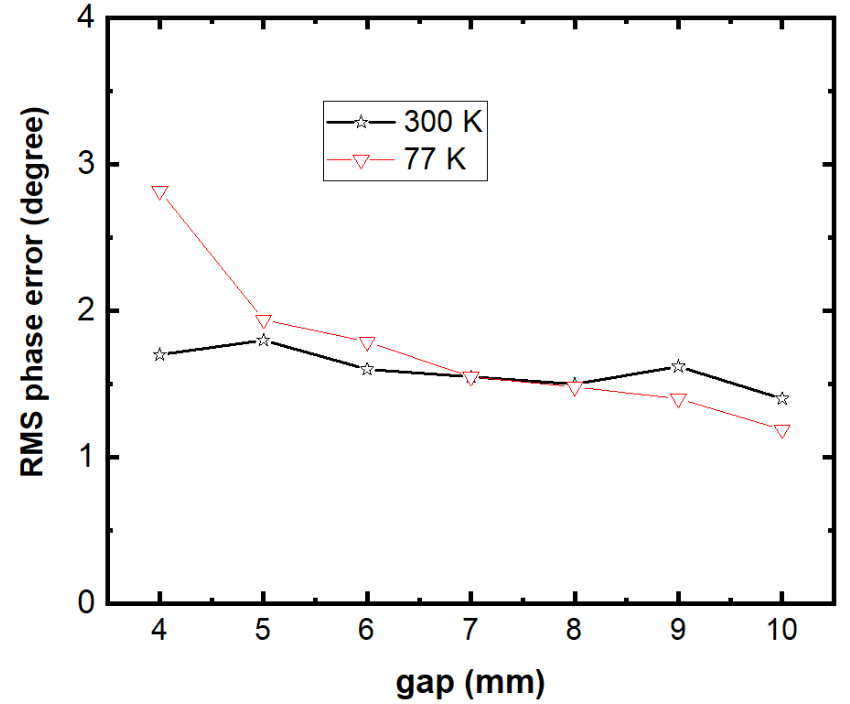





- Four spring modules attached to the out of vacuum girders.
- A program predict the amount of adjustments
- First tune spring modules at a gap of 11 mm (weakest spring starting engaging) then close gap to each spring engaging point and tuning.
- A Hall probe reads the field strength during tuning.

# Field performance after tuning




- The error storage can be reduced to be smaller than ± 2 % by using these two methods.
- After several tuning steps, the RMS phase errors could be reduced to below $2^0$ at 77 K and a gap of 5 mm

# Summary

- A cryogenic undulator with period length of 15 mm are constructed for the TPS beamlines.
- Several methods, including spring modules, differential adjusters, temperature control system, are applied to ensure the field performance.
- The in-situ measurement system is improved to do the measurement at low temperature.
- Field tuning methods are necessary to keep low phase errors after the vacuum chamber installed and cooling the magnetic array down.

***Thank you for your attentions***

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