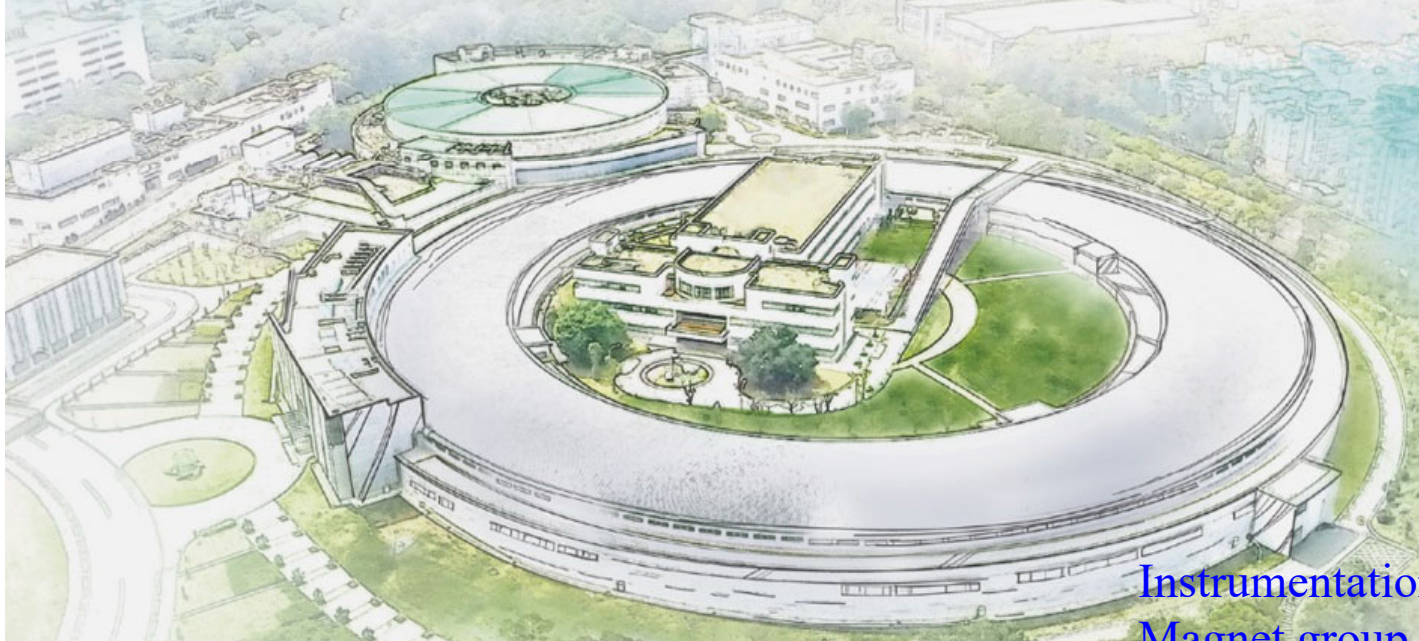

國家同步輻射研究中心
National Synchrotron Radiation Research Center

# Tapered APPLE undulators at TPS



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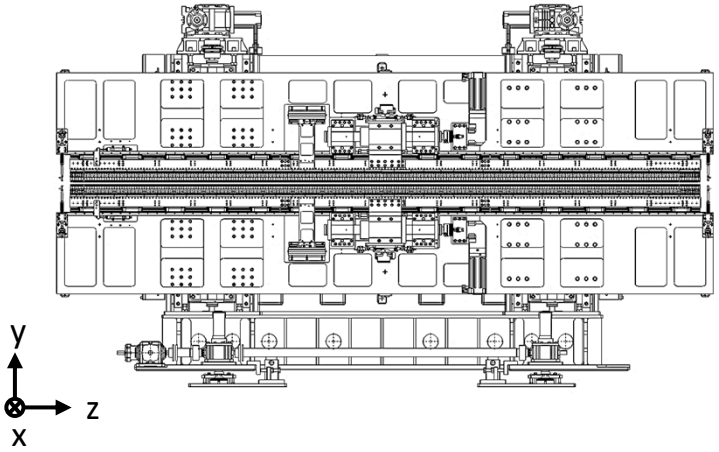
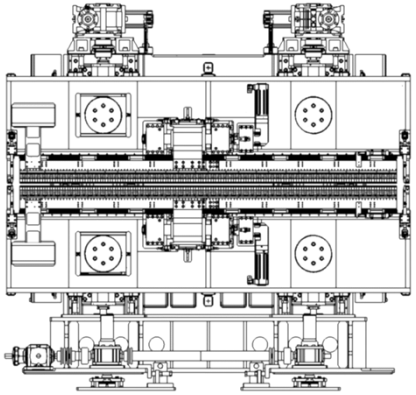
# APPLE EPU at TPS

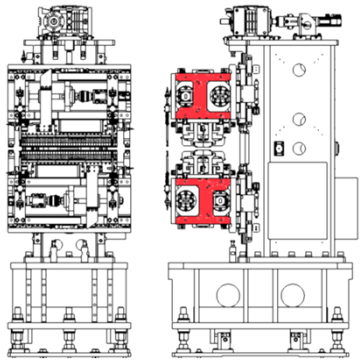
The NSRRC has designed and constructed nine APPLE EPUs of various configurations.

| | Beamline at TPS | Length(m) | Remarks |
|---|---|---|---|
| EPU66 | 27 | 4.4 | Operation |
| EPUT66 | 33 | 2.6×2 | Tandem taper EPUs. Construction in progress, to be installed in 2027. |
| EPU66s | 35 | 0.8 | Operation |
| EPU168 | 39 | 4.4 | Operation |
| EPU48 | 41 | 3.4×2 | Operation |
| EPU56 | 43 | 4.4 | Operation |
| EPU66N | 45 | 4.4 | Construction completed, to be installed in 2026. |



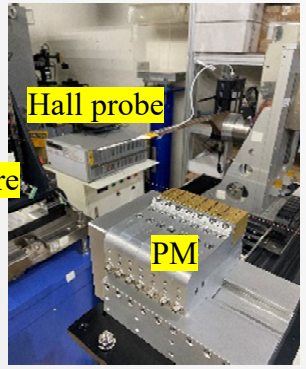



The 2.6m taper EPU is the main focus of today's presentation.



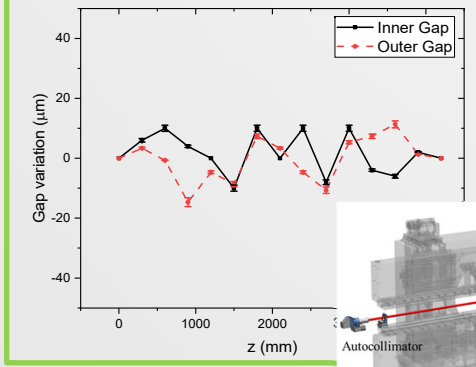
# Construction technologies: Magnetic field optimization

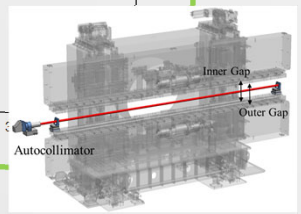
Optimizing light intensity : electron trajectory, phase error and quadrupole errors.



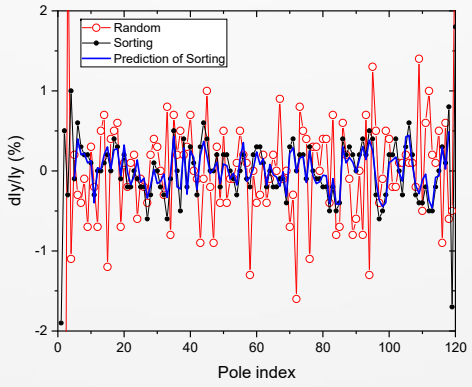

Magnetic properties of submodules

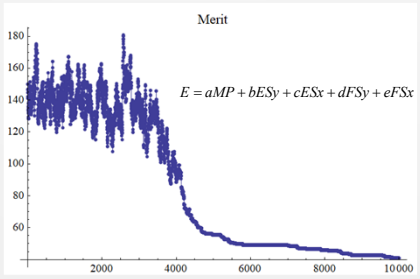
Mechanical properties of girders



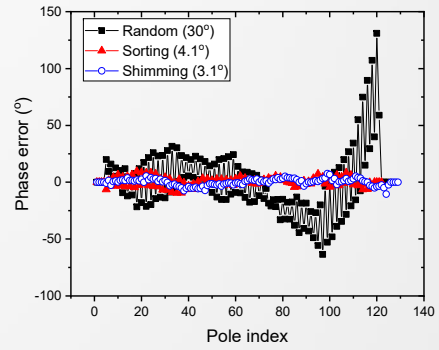



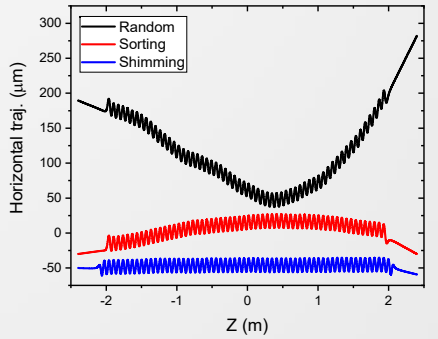

Sorting and shimming.

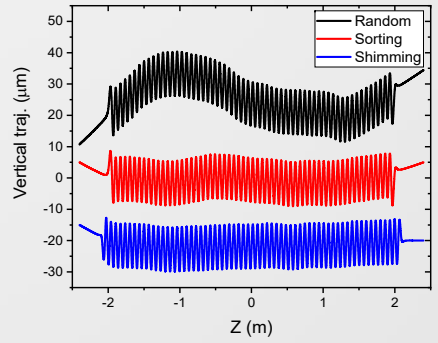



Simulated annealing algorithm



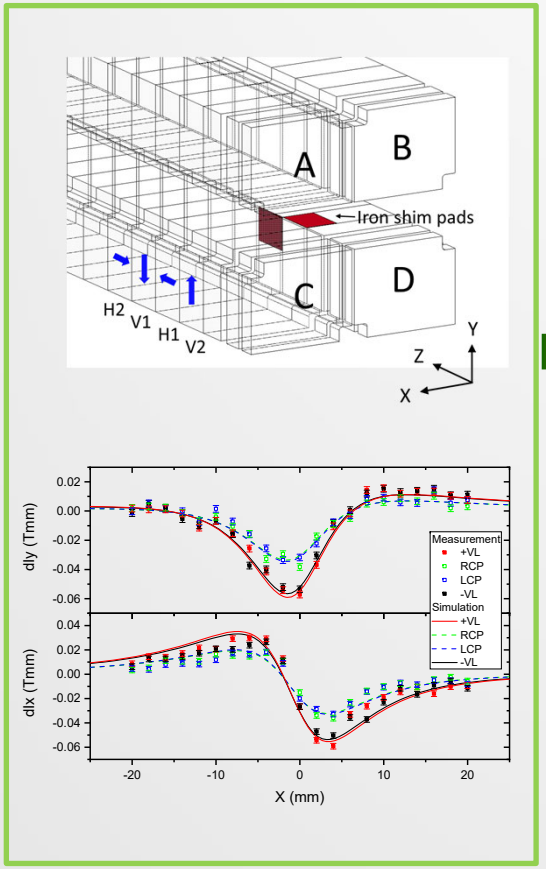



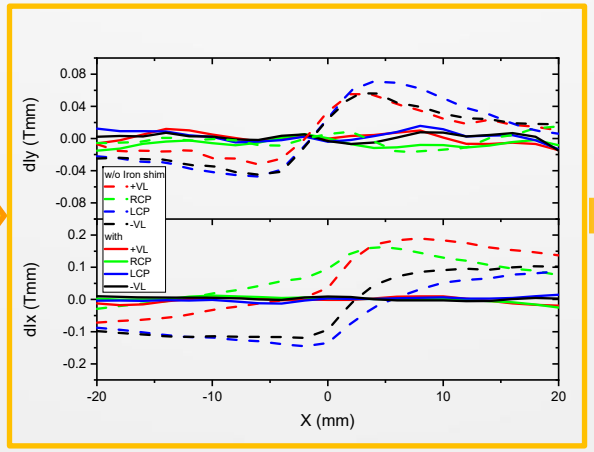
# Construction technologies: Magnetic field optimization

Reducing adverse effects on a ring : phase dependent and independent multipole errors.

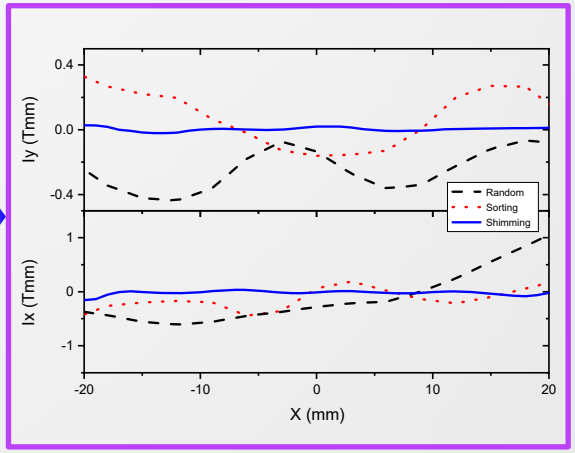
The nonlinear compensation with iron shim pads.




Phase dependent multipoles




Phase Independent multipoles

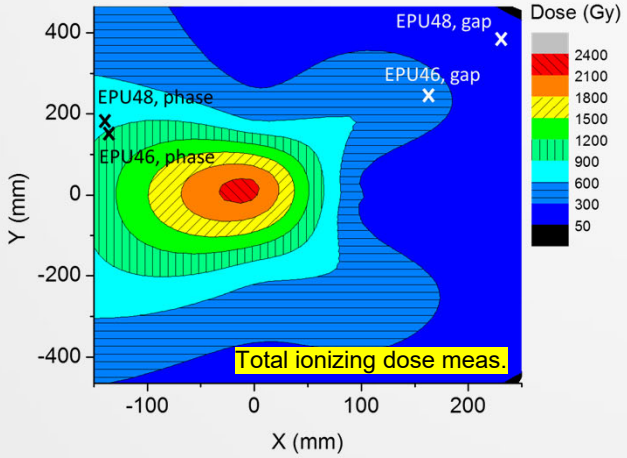


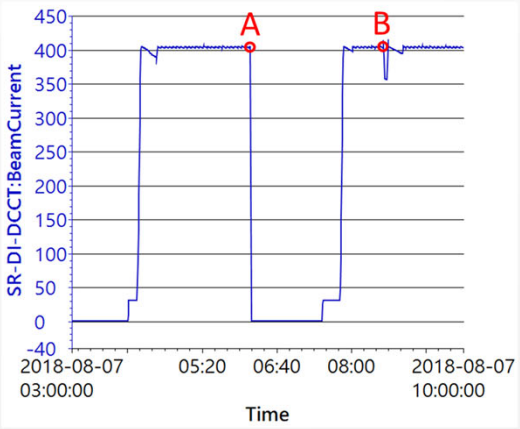

- The PD terms could be lowered to ±0.015Tmm.
- The PID terms are within ±0.03Tmm

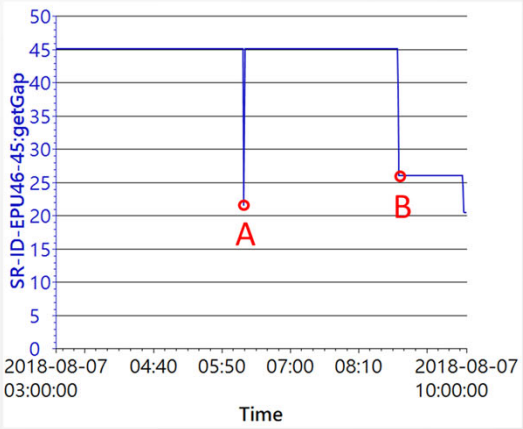
# Experience of operation of EPUs at TPS

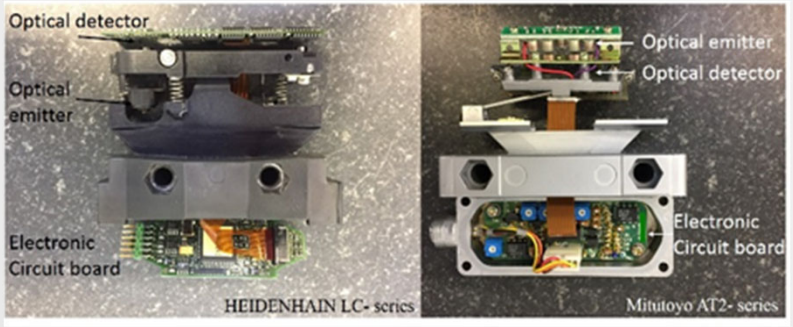
Radiation issue : a malfunction of driving system is found to follow an electron beam dump or loss.

⇒ Encoders, contain semiconductor devices, have soft errors by radiation damage.



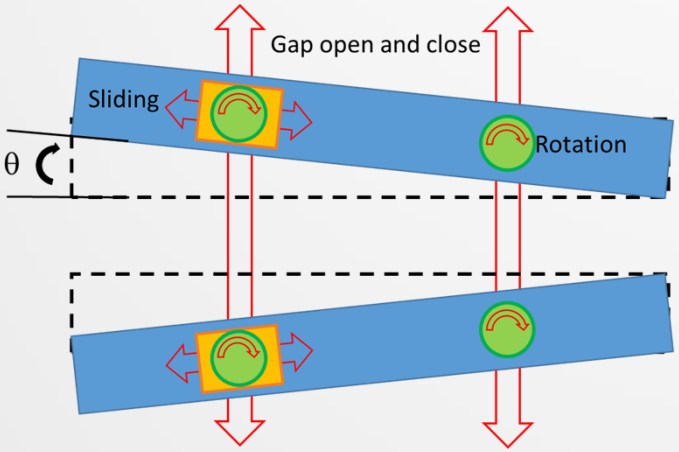




NSRRC strategies,

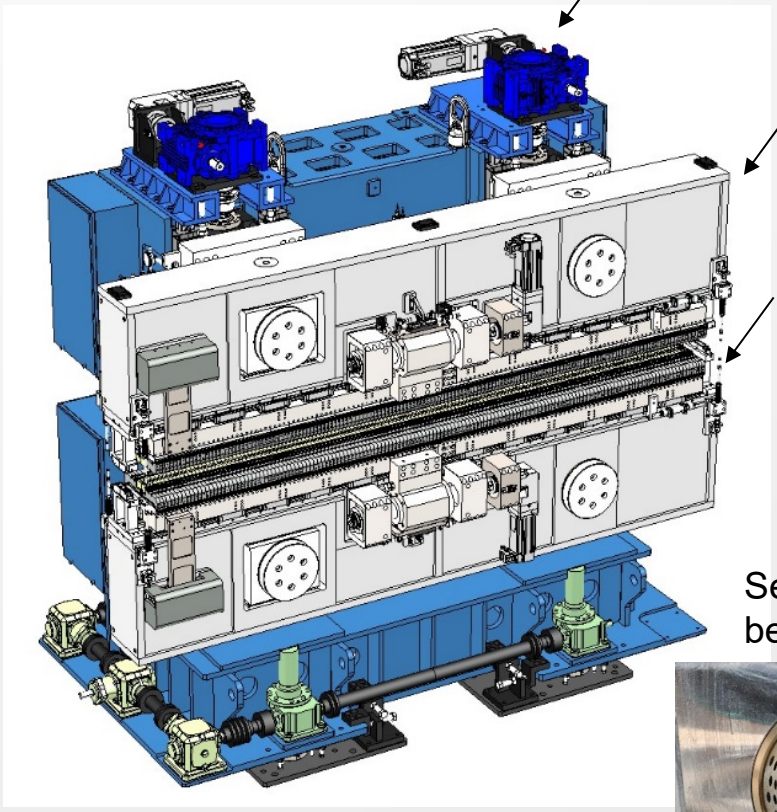
- Reduce the number of electronic components in the drive system.
- Shield encoders.
- Increase their distance from the electron beam.
- Introduce linear displacement sensors without semiconductor components.

# Parameter and Structure of Tapered APPLE

- Left- and right-hand ball screws are connected in series to change a gap.
- The upstream–downstream gap difference forms a taper through rotation and sliding of self-lubricating bearings.




| | | |
|---|---|---|
| Period length | 66 | mm |
| Number of period | 36 | |
| Physical length | 2392.5 | mm |
| Mini. gap | 16 | mm |
| Max. Taper (2θ) | 4 | mrad |
| Max Ver. gap diff. | 10.6 | mm |
| Max. Hori./Vert. magnetic field | 0.63/0.86 | T |
| Permanent magnet (Br) | 1.24 | T |




Self-lubricating bearings

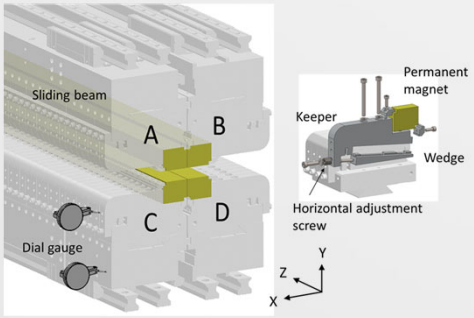
# Mechanical construction

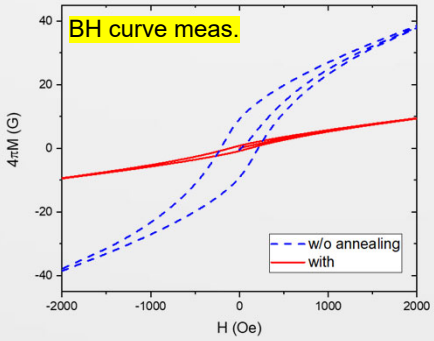
Material and machining inspection

- Removal of residual magnetism in the backing beam: Annealing and AC field demagnetization using coils and surface demagnetizers before assembly.
- The materials closer to the electron beam need to undergo demagnetization treatment while still meeting the required mechanical strength for the design.

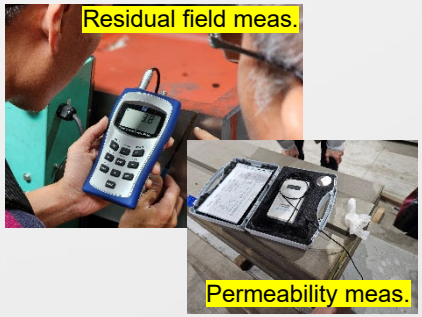

Backing beam


Annealing fixture and perform BH curve using VSM.




Sliding beam

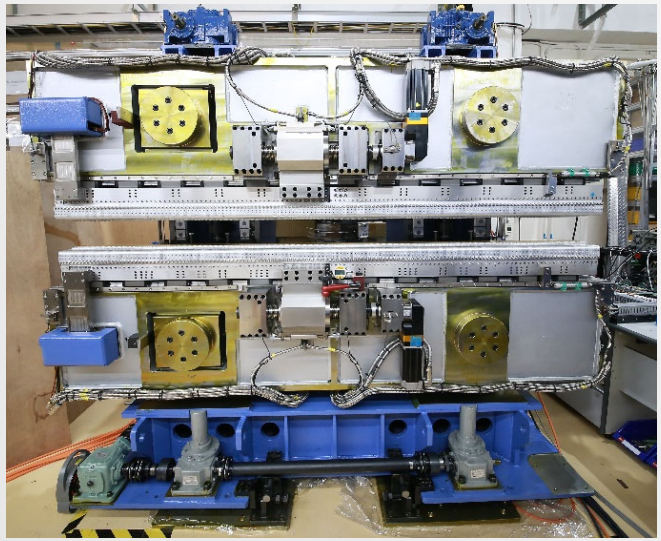


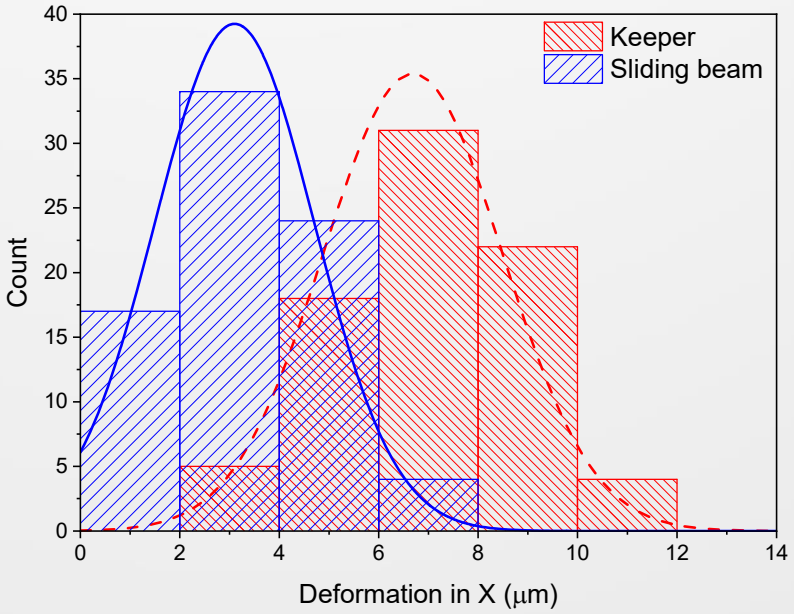

Tensile tests

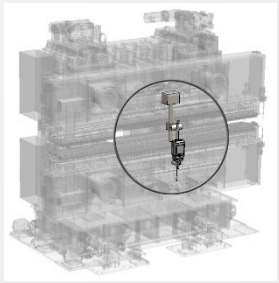
# Parallel mode _ Mechanical inspection

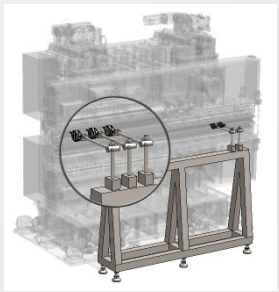
The operation that withstands the maximum force is also the typical operating condition of the EPU.

- The gap variation within ±20 μm.
- Phase actuation, the deformation in the x-direction ~ 6.7/3.3 μm for the keeper/sliding beam.
- Gap actuation, repeatability ~1.4 μm (±2σ) for the open-loop control; while submicron under closed-loop control.





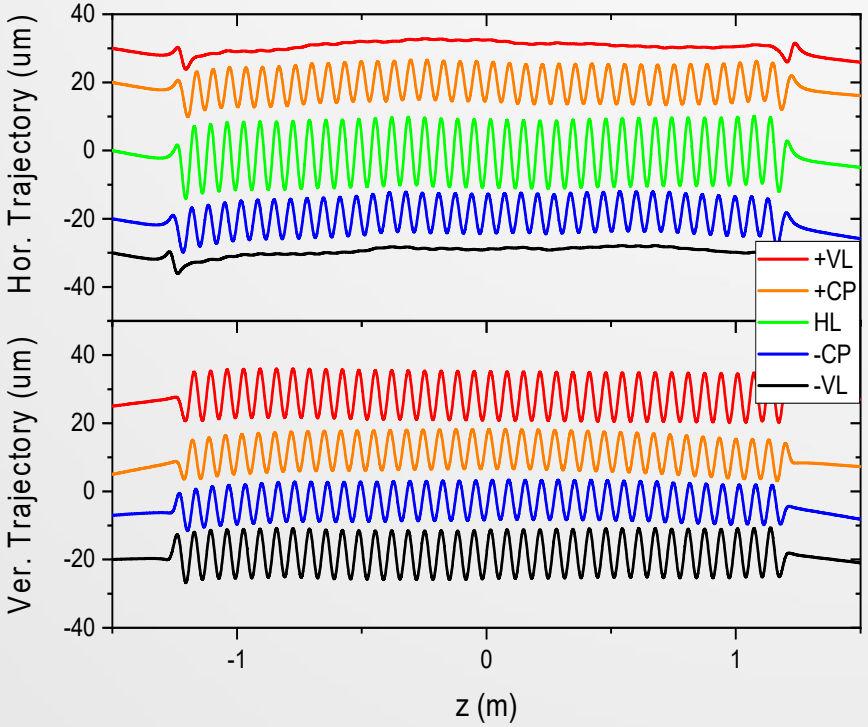



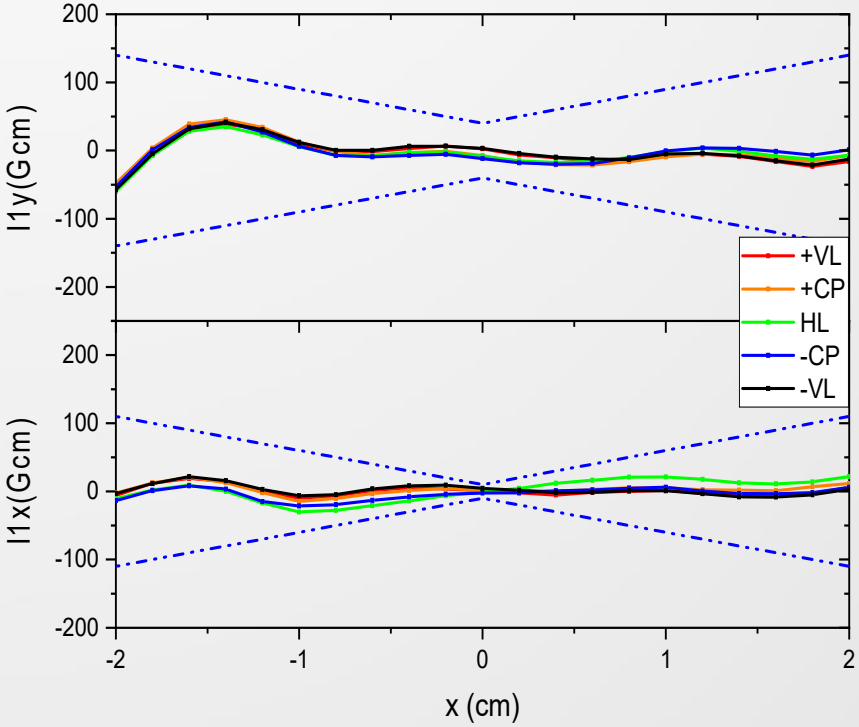


# Parallel mode _ Magnetic properties

- Phase error within specification.
- Trajectory well controlled.
- Field integrals meet TPS requirements.

| | Phase error (degree) | | |
|---|---|---|---|
| | Bef. Sorting | Aft. Sorting | Shimming |
| HL | 10.11 | 3.35 | 1.82 |
| VL | 6.15 | 1.42 | 1.22 |

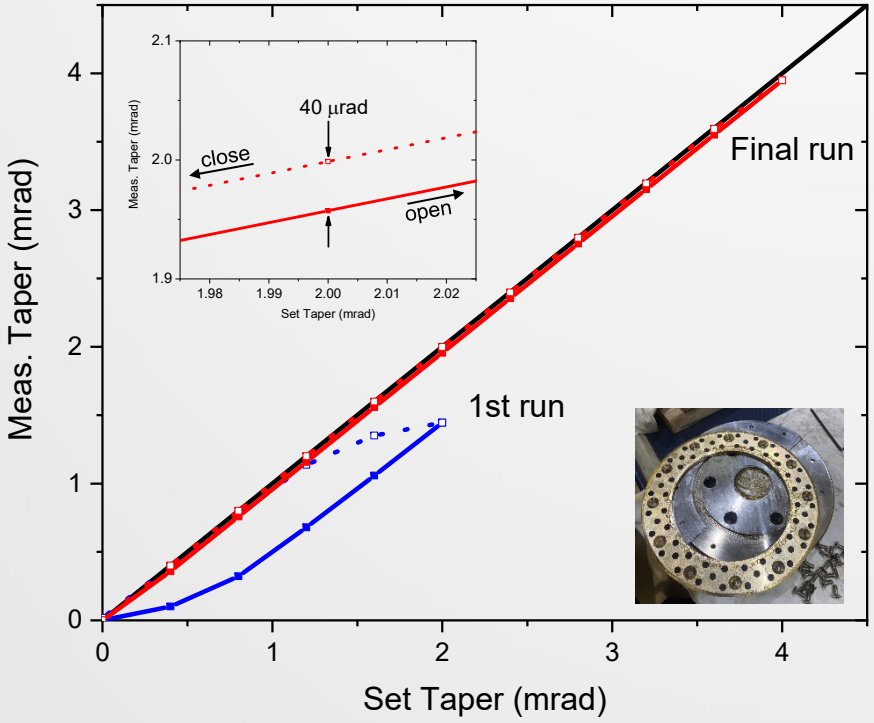


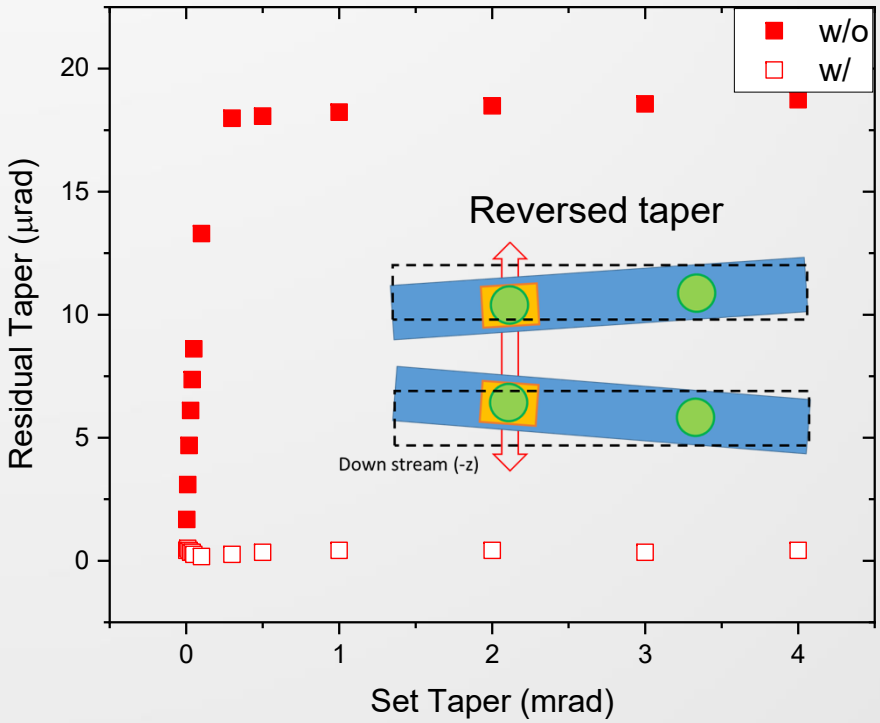



# Tapered mode _ Mechanical inspection

- Fix the upstream gap drive system, and open/close the downstream gap.
- Mechanical hysteresis,
  => adjust the shim thickness and perform scraping (~40 μrad).
- Residual taper when returning from tapered to parallel mode (<18 μrad).
  => to eliminate through reversed taper.

The issue is under evaluation for mitigation via encoder installation on the backing beam with closed-loop control. (In progress)

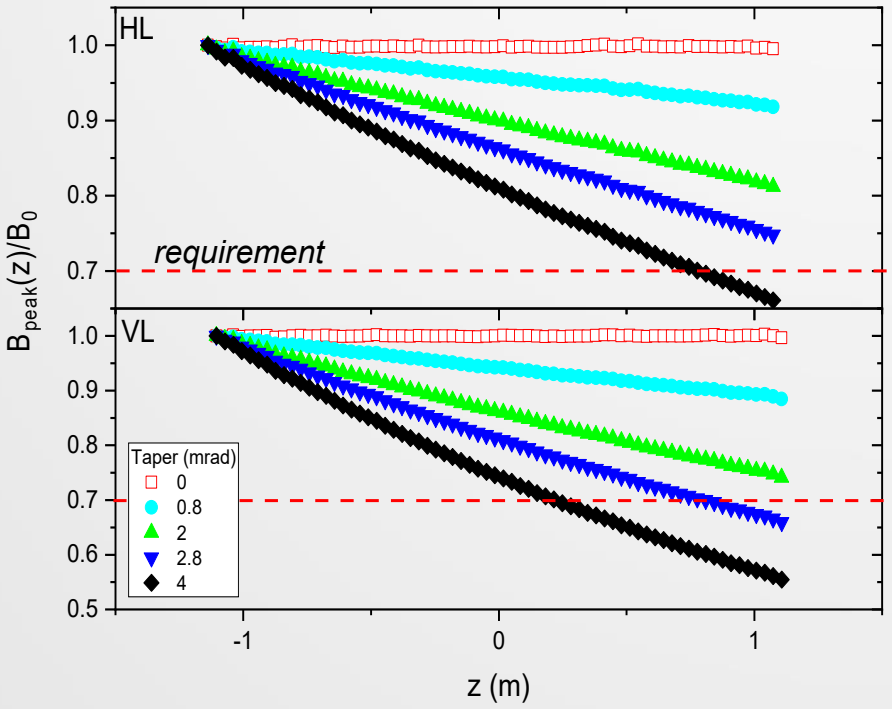


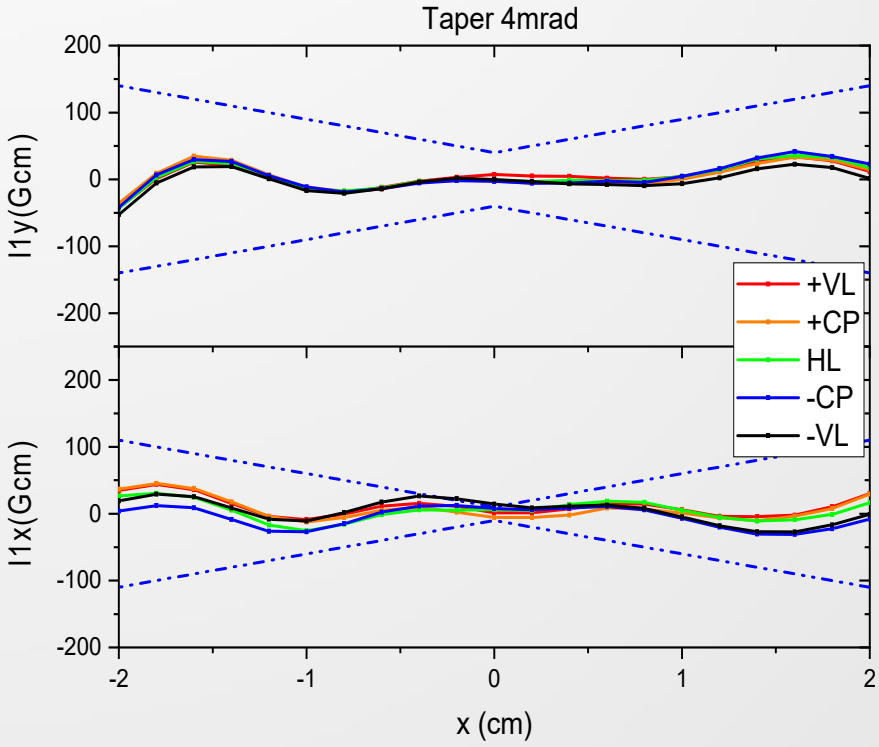



# Tapered mode _ Magnetic properties

Magnetic field measurements confirm that tapered mode operation is repeatable and that parallel mode shows no residual taper.

- 4 mrad taper satisfies the user requirement for spectral broadening.
- Compared to parallel mode, the dipole term of I1x in the 4 mrad taper slightly exceeds the specification; this can be corrected using a corrector.



# Conclusions

- Tapered APPLE EPU developed at NSRRC.
- Mechanical and magnetic performance meet TPS requirements.
- Tapered mode enables spectral broadening.
- Remaining issue: mechanical hysteresis under investigation.

*Thank you so much for your attention.*