Eight-piece quadrupole magnet tolerance analysis*

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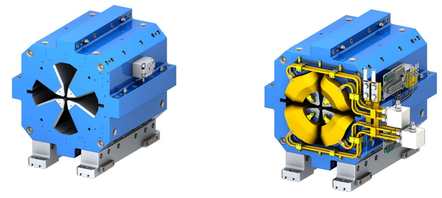


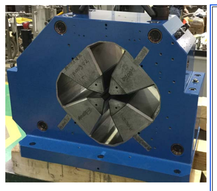
Background

Early R&D magnets for the APS Upgrade project were built based on a conventional two-piece quadrupole magnet design. However, the as-assembled magnets showed high multipole errors and magnetic center offsets that were out of specification. An eight-piece quadrupole design and assembly method is developed that produces the desired magnetic field quality and can be manufactured cost-effectively.

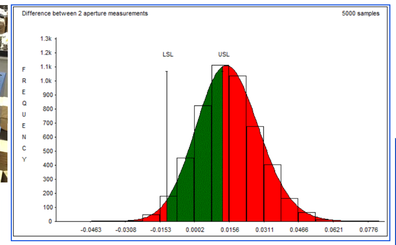
Objectives

- **Identify the key features that affect the magnetic field quality in both two-piece and eight-piece quadrupole magnet designs.**
- **Determine the appropriate tolerances for the identified key features in both quadrupole magnet designs.**
- **Select the design and the proper machining and assembly tolerance level for APS Upgrade storage ring.**

Conventional Two-Piece Quadrupole R&D Magnets



Two-piece Quadrupole Yoke assembly

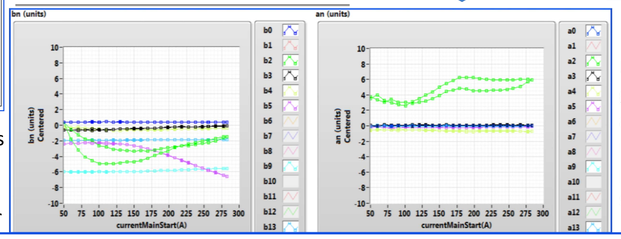


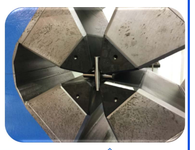
- Intrinsically has big tolerance stack-up on final pole tips locations,
- High lower order harmonics
- Big offset between magnetic center from the mechanical center

DIFFERENCES IN APERTURES AND POLE TIP GAP SIZES AT DIFFERENT TOLERANCE LEVELS

Part tol. (mm)	Aperture diff. mean (mm)	Aperture diff. Std. Dev. (mm)	Gap size diff. Mean (mm)	Gap size diff. Std. Dev (mm)
0.025	0.015	0.014	0.004	0.095
0.05	0.024	0.027	-0.004	0.187
0.1	0.049	0.053	-0.008	0.375

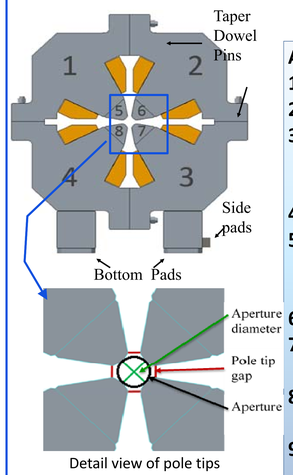
Measurements show satisfactory results after re-alignment of pole tips.





Use Criss-Cross gauge pins and a center pin to re-align magnet pole tips to be symmetric.

New Eight-Piece Quadrupole R&D Magnets

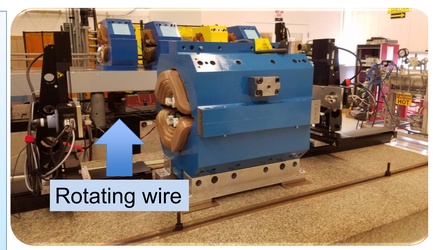


Detail view of pole tips

- Four pole tips will be symmetry within 25 µm
- The aperture could change
- The gap could change

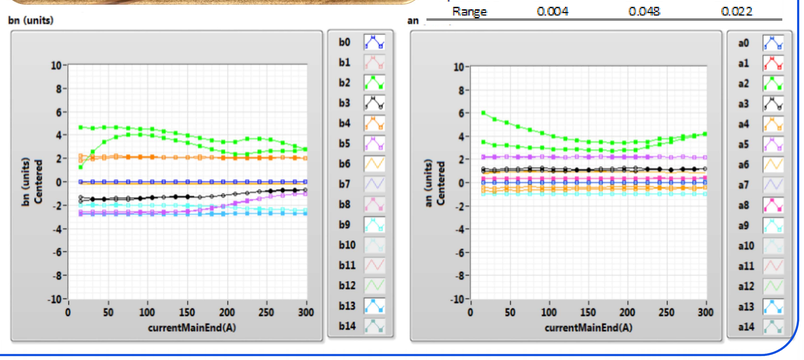
Alignment Steps:

1. **Assemble magnet as is;**
2. **Measure aperture diameters;**
3. **Average measurements and subtract 10 µm to select center gauge pin;**
4. **Measure pole tip gaps;**
5. **Average measurements and subtract 10 µm to select criss-cross gauge block;**
6. **Loosen clamping screws**
7. **Insert center pin in the aperture;**
8. **Insert criss-cross gauge blocks in pole tip gaps at both ends;**
9. **Tighten the clamping screws to the specified torque;**
10. **Drill and ream taper dowel pin hole on the mating flanges;**
11. **Apply metal-filled epoxy to the pre-machined key slots.**

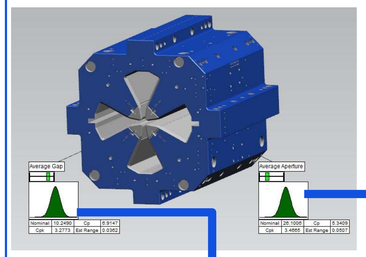


EIGHT-PIECE R&D MAGNET YOKE ASSEMBLY MEASUREMENT

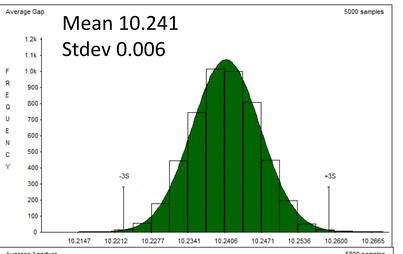
	Up-stream (mm)	Down-stream (mm)	Average (mm)
Gap 1	10.343	10.314	10.3285
Gap 2	10.326	10.333	10.3295
Gap 3	10.318	10.295	10.3065
Gap 4	10.341	10.291	10.316
Max	10.343	10.333	10.3295
Min	10.318	10.291	10.3065
Range	0.025	0.042	0.023
Aperture 1	26.141	26.090	26.1155
Aperture 2	26.137	26.138	26.1375
Range	0.004	0.048	0.022

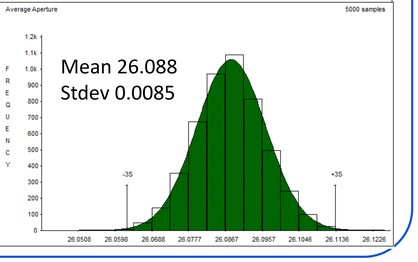


Mechanical Tolerance Stack-up Analyses



- TcVis Variation Analysis
- Virtually making parts per print
- Virtually assemble parts
- Virtually measure parts
- Simulate using Monte Carlo Method



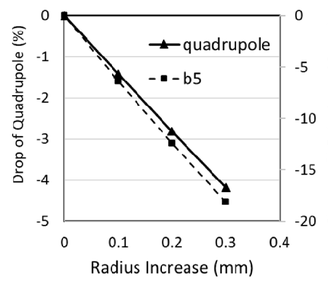


APERTURE AND GAP SIZES AT DIFFERENT TOLERANCE LEVELS

Part tol. (mm)	Aperture mean (mm)	Aperture Std. Dev. (mm)	Gap size Mean (mm)	Gap size Std. Dev. (mm)
0.025	26.044	0.035	10.209	0.067
0.050	26.079	0.094	10.241	0.133
0.100	26.177	0.140	10.306	0.267

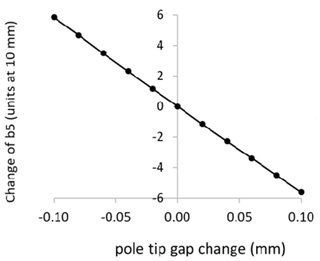
Magnetic Tolerance Analyses

The effect of Aperture Size change



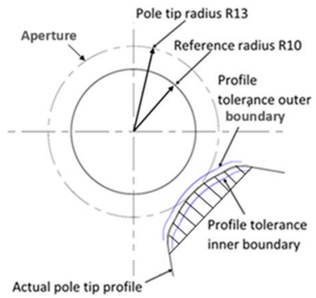
- Aperture size change will affect both main field and 12-pole
- Acceptable aperture is 26 mm to 26.271 mm

The effect of gap Size change



- Change in gap size will affect 12-pole
- Acceptable aperture is 10.05 mm to 10.30 mm

The effect of surface profile error



- Pole tip surface profile error will affect sextupole
- Acceptable profile error is 30 µm

Conclusions

- **The key feature that affects the magnetic field is identified to be the symmetry of the four pole tips around the quadrupole longitudinal axis**
- **With a conventional two-piece design quadrupole, even 25 µm machining error will result in excessive stack-up tolerances and hence deteriorated magnetic field quality. With eight-piece design, 50 µm standard machining precision is sufficient to make high quality magnet**
- **Eight-piece design and 50 µm machining tolerance will be selected for APS Upgrade quadrupole magnet**

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