Design of Split Permanent Magnet Quadrupoles for Small Aperture Implementation

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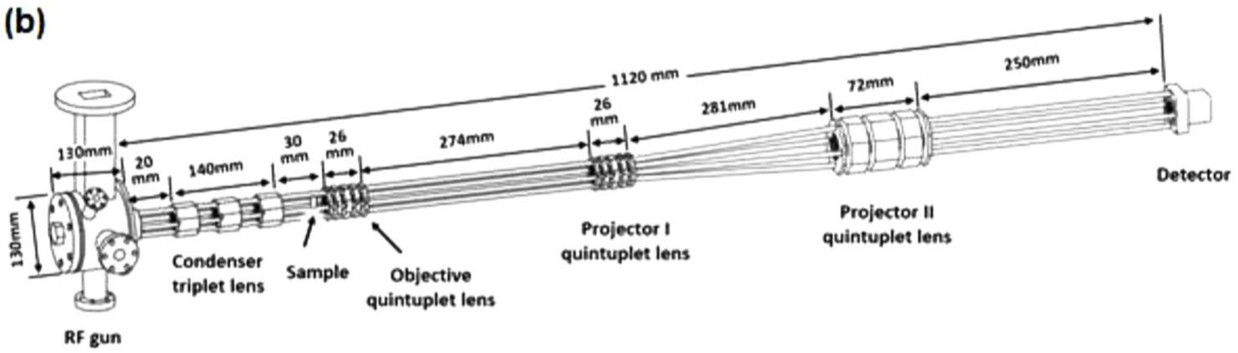
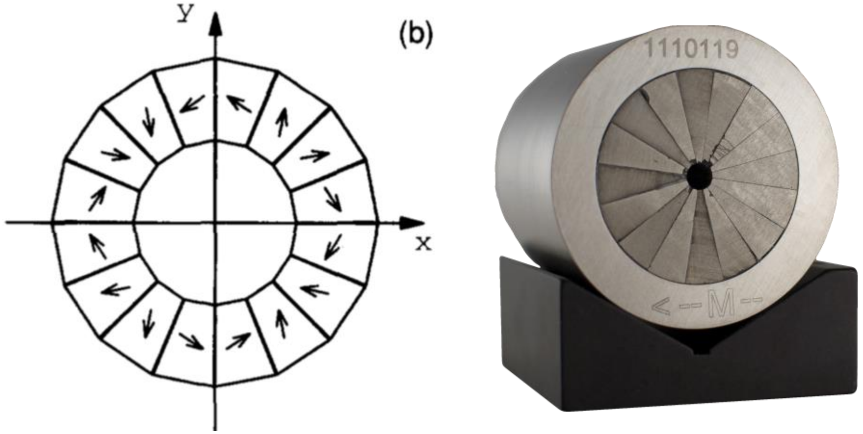
Background: Ultrafast Electron Microscopy

- UEM at high energy (3 MeV)
  - Reduces space charge forces in electron beam
- Strong focusing with permanent magnet quadrupoes (PMQ)
  - Provide high focusing gradients in a compact footprint
  - Since quads focus in one dimension and defocus in the orthogonal, the optic must be a multiplet to produce a round lens
- Optimization scheme arrived at a quintuplet design
  - See Chris Hall's poster (MOPAB249) for details on the multi-objective optimization algorithm (MOGA)



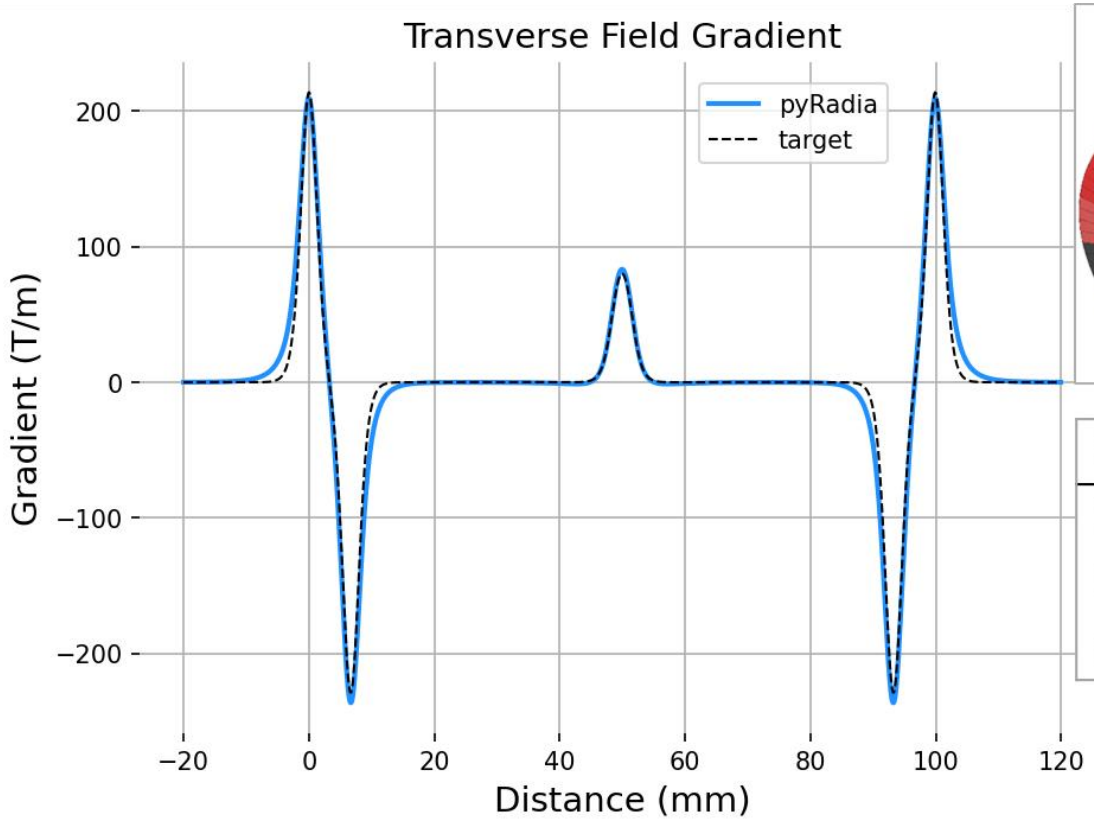
Wan, Chen, Zhu, *Ultramicroscopy* **194**, 143 (2018)

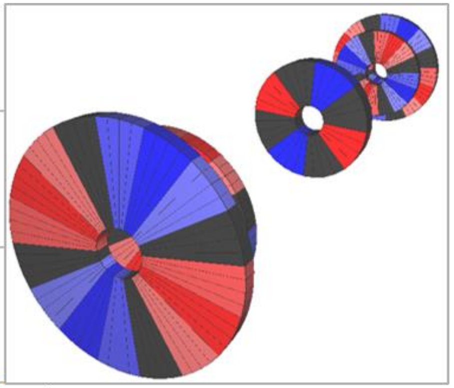


Halbach, *Nucl. Instrum Methods* **169**, 1-10 (1980)

Quintuplet design

- Optimization scheme arrived at a quintuplet design
  - See Chris Hall's poster (MOPAB249) for details on the multi-objective optimization algorithm (MOGA)
- MOGA quadrupole properties:
  - Big aperture (r~2.5mm), short length (L~2mm, and high gradients (~200T/m)
- Shown are the target gradient profile and that achieved from an engineering informed design with pyRadia (https://github.com/ochubar/Radia)
- The 3D magnetostatic simulations (blue line) achieve the required peak gradient
  - But produce heavier fringe tails than the target (first order Enge model – dashed line)
  - The large aperture-to-length ratio introduces large 3D effects

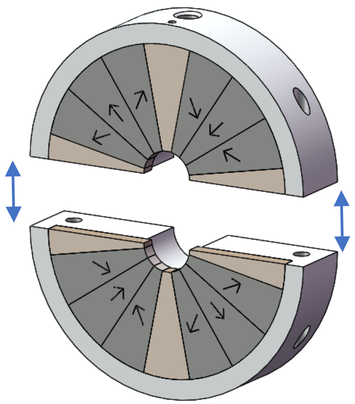


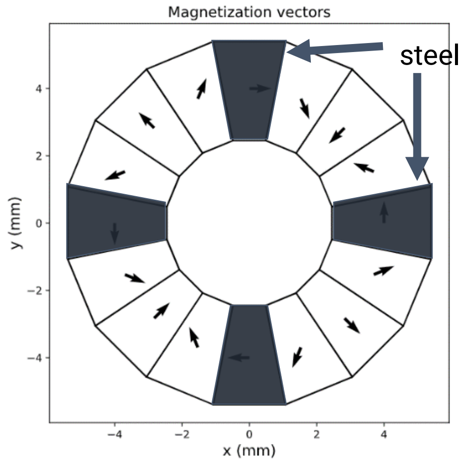


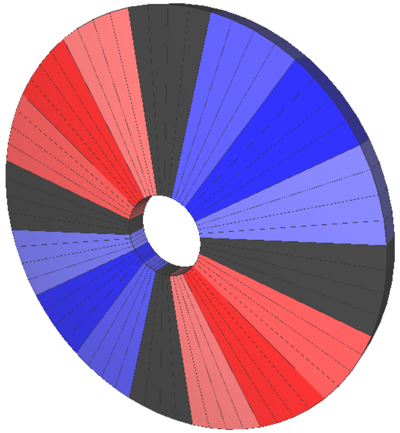
Peak gradients (T/m)	
Quad 1 & 5	214
Quad 2 & 4	229
Quad 3	80

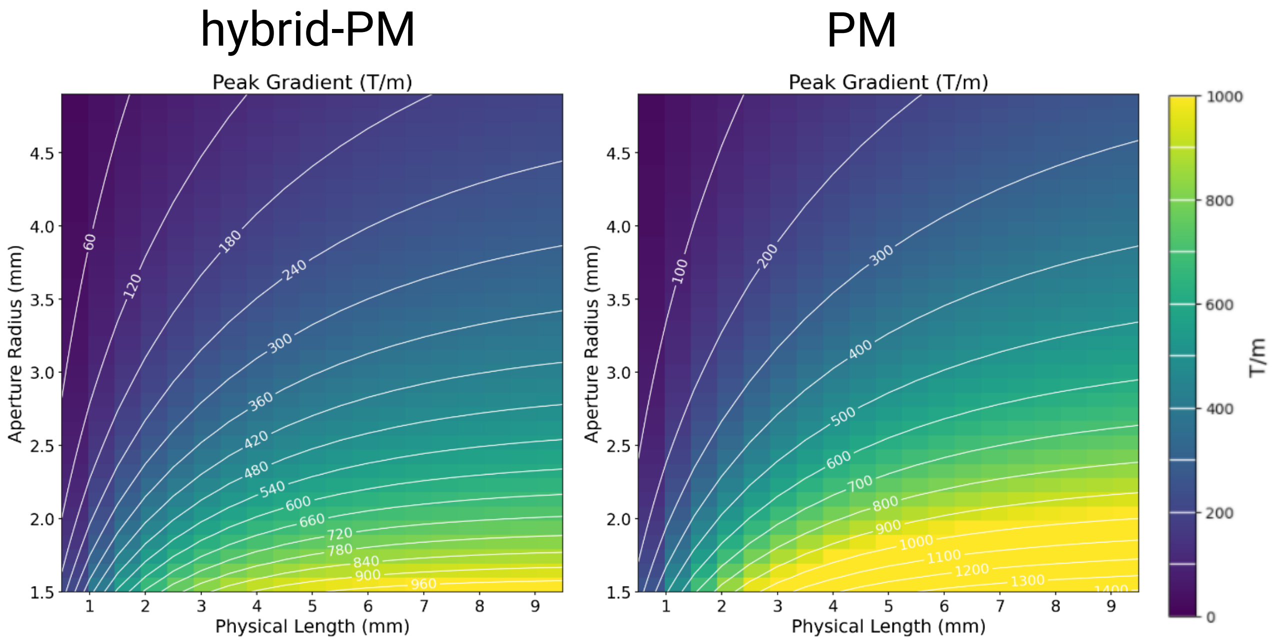
“Splittable” hybrid PMQ design

- In order to place the quadrupoles around the electron beam chamber a splittable design was introduced
- Steel blocks replace 4 of the PM blocks
  - The steel is easily cut and allows the hybrid-PMQ to be mounted around a chamber
  - Allows the quads to remain outside of vacuum
  - Quads are removable without changing the electron beam chamber
- Peak gradient is reduced since PM volume is replaced with steel



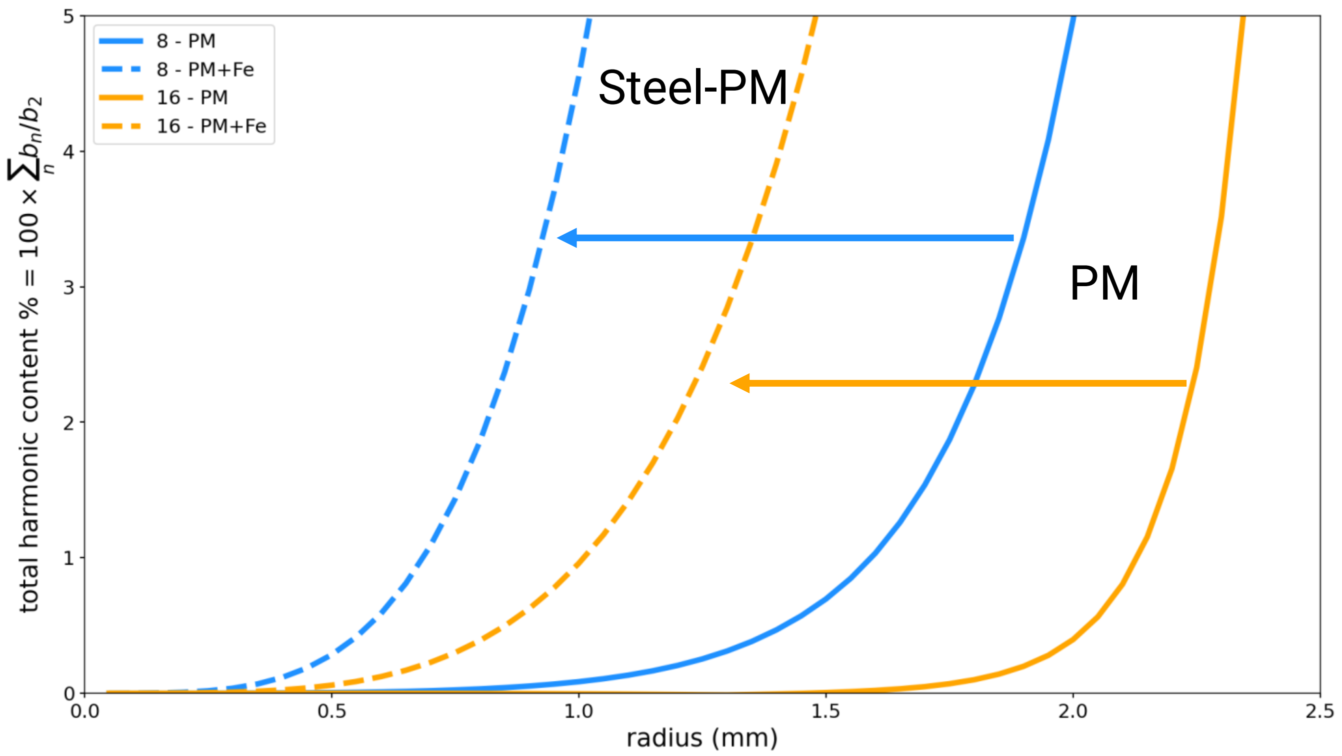






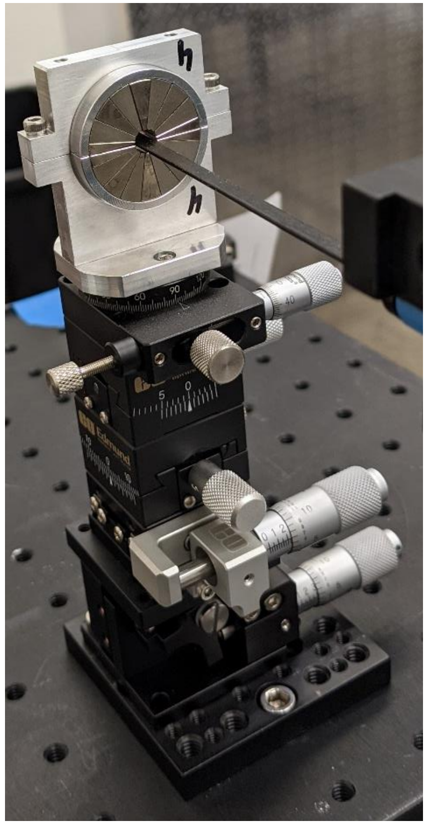
Degradation of Harmonic Content

The introduction of steel in the design increases the non-quadrupole moments inside the aperture

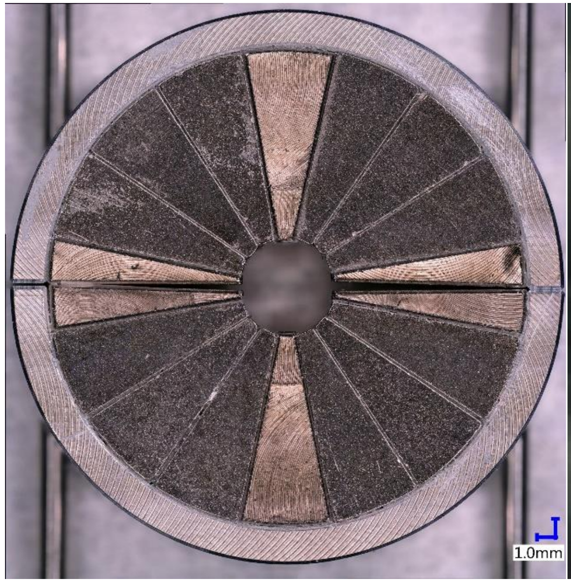


Manufacture and Measurement

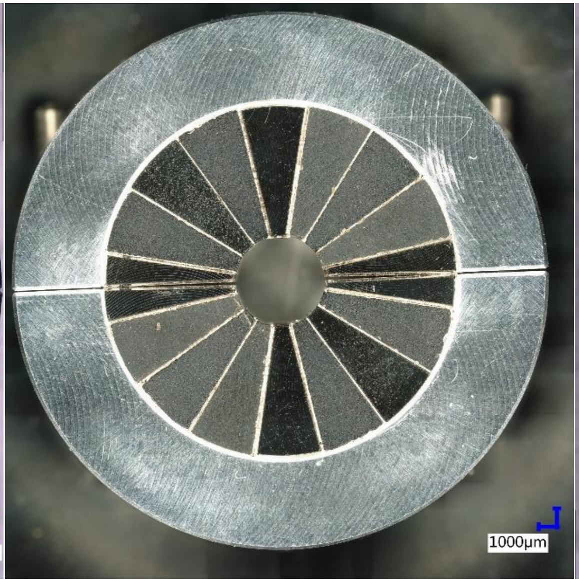
- RadiaBeam has manufactured the 3 different hybrid-PMQs outlined in the quintuplet optic design
- Hall probe measurements were undertaken to qualify the magnetic characteristics of the quadurpoles



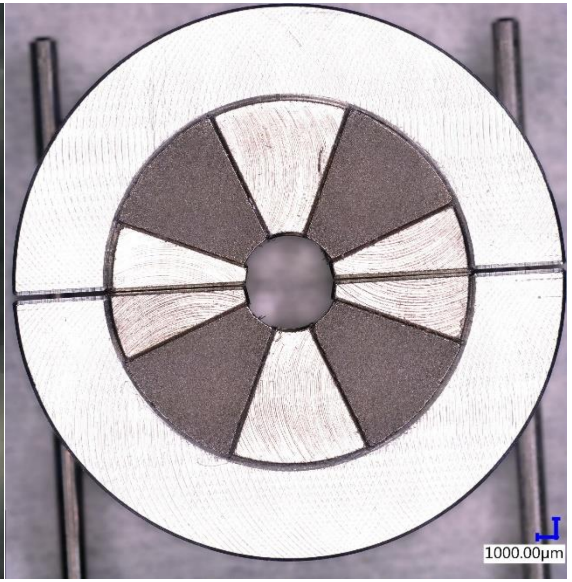
Hybrid-PMQ type 1



type 2



type 3



Gradient Profile Measurements

RadiaBeam

- Measured gradient profiles are presented for 6 samples of hybrid-PMQ type 1
- The measured peak gradient is far below the peak gradient reached in 3D magnetostatic simulations
  - This is expected in the manufacture of such small assemblies as tolerance stack-up becomes large
- The physical length of the manufactured quadrupoles is 6 mm
  - Target magnetic length was 1.5 mm with a peak of 214 T/m
- Intent is to cut the quadrupoles to size in order to achieve desired magnification and resolution from full optic
  - New MOGA optimizations are under way

```
mean(gby_max)  = 243.610 T/m
std(gby_max)   = 13.498 T/m
mean(int(gby)) = 1.975 (T/m)*m
std(int(gby))  = 0.081 (T/m)*m
mean(mag len)  = 8.11 mm
std(mag len)   = 0.11 mm
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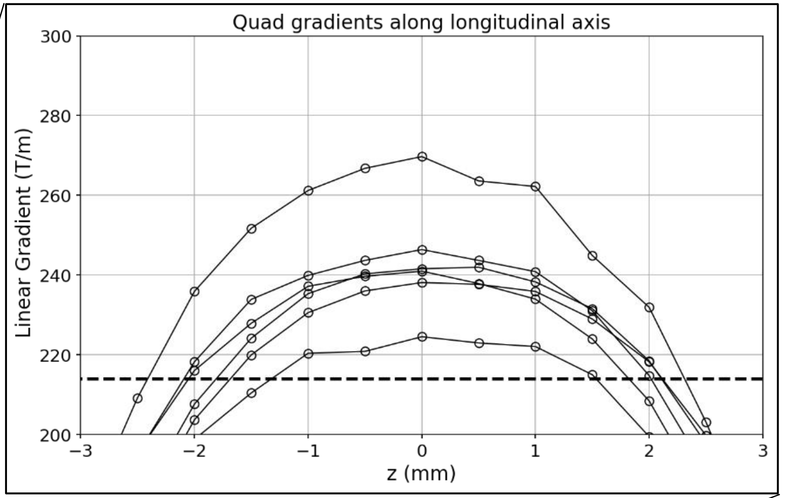
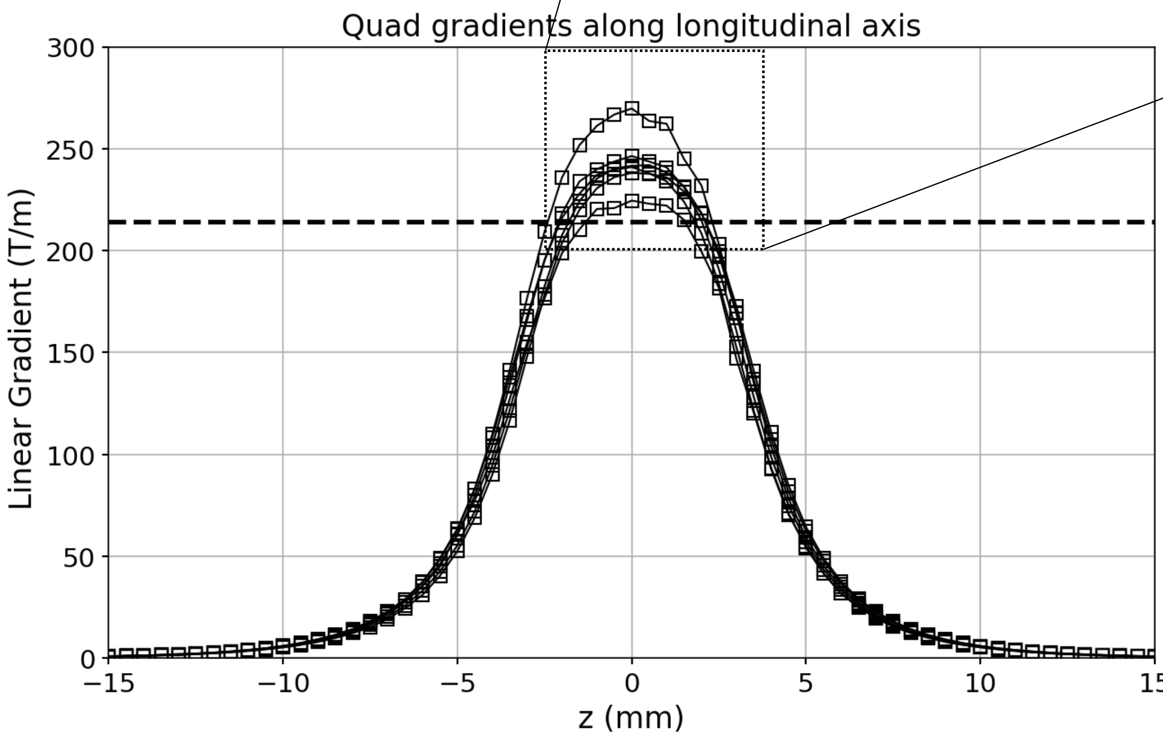
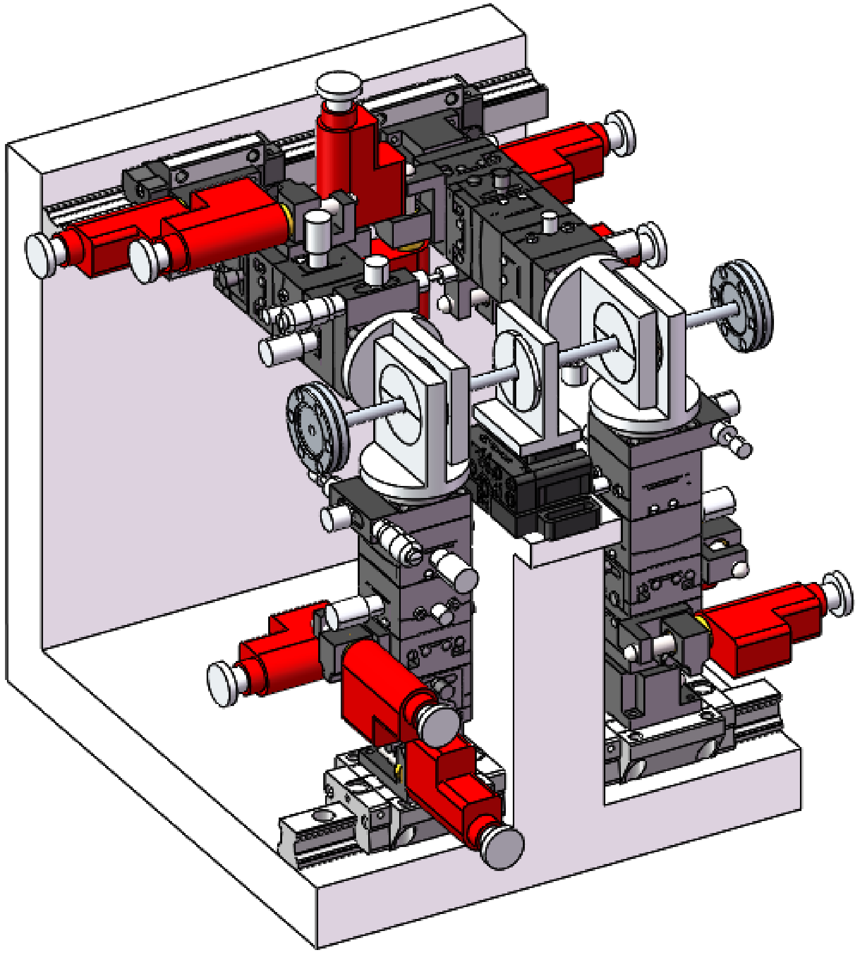




Outlook

- Measurement of the quadrupole gradients will be fed back into the MOGA optimizer (C. Hall, RadiaSoft, MOPAB249) in order to produce a sensible quintuplet optic
- Assembly and self-alignment of the full quintuplet will then proceed
- Experimental runs are planned at the Brookhaven National Lab's UED facility (G. Andonian, RadiaBeam, MOPAB139)



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