Permanent Magnet Quadrupoles for Microscopy Systems

ATF Users Meeting
12/09/2020

Proposal ID: #308089
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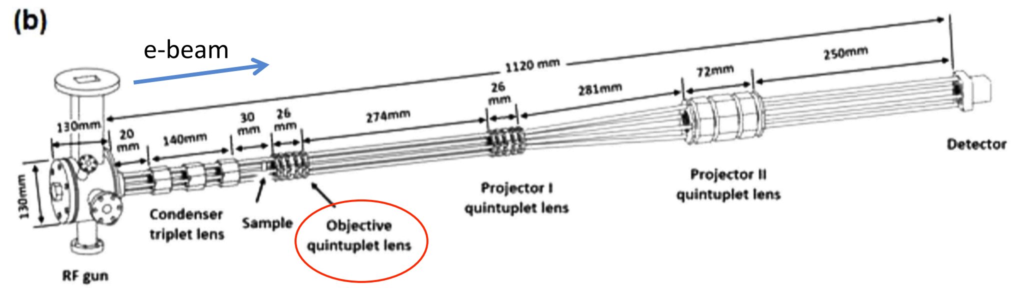
Funding source: DOE SBIR
Status of funding: Received (follow-on proposal in prep.)

Instructions for UED Proposal Presenters

- All ***"Proposal"*** presentations are 20 minutes in duration: 15' presentation + 5' questions
- Proposal Title Slide - Please include:
  - Proposal ID & Proposal Title
  - PI Name
  - A list of all collaborators and institutions
  - Funding source
  - Status of funding ("Proposed" or "Received")
- The following 2 slides provide summary information for UED User Experiments in a ready-to-use format for the Program Advisory Committee and ATF Management. Please include them at the end of your presentation
  - [Slide 1] Please fill out the "Special Equipment Requirements and Hazards" slide for your experiment
  - [Slide 2] Please fill out the "Experimental Time Request" slide for your experiment
  - ***To save time during presentations, you do NOT need to present these slides unless there is something very important you want to emphasize. Please just make sure they are attached to the end of your presentation.***

Background

- UEM at high energy (3MeV)
  - Reduce space charge forces
- Strong focusing PMQ vs solenoid
  - Compact with high fields
  - PMQ asymmetric focusing, requires multiplet for round lens
- Multiplet design (quintuplet) for objective lens
  - High Magnification
  - low aberration
  - extra degrees of freedom
- Drop in to UEM/BNL project

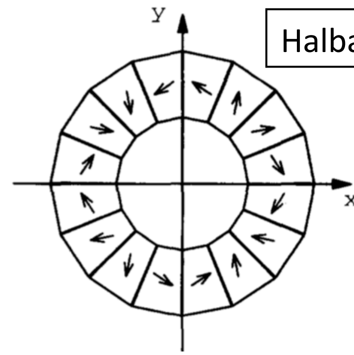


Wan, Chen, Zhu, *Ultramicroscopy* **194**, 143 (2018)

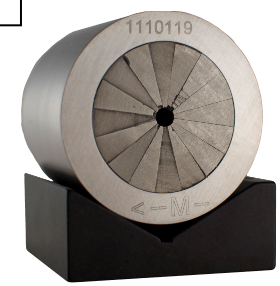
Permanent Magnet Quadrupole

- PMQs can achieve high fields in compact forms
- Halbach quadrupole
  - Segmented wedges
  - Decreasing r_i increases gradient
  - Increasing segments increases gradient, field quality
  - Thin PMQs require, larger r_o
- Experience from other applications
- Small apertures require strict alignment tolerances

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

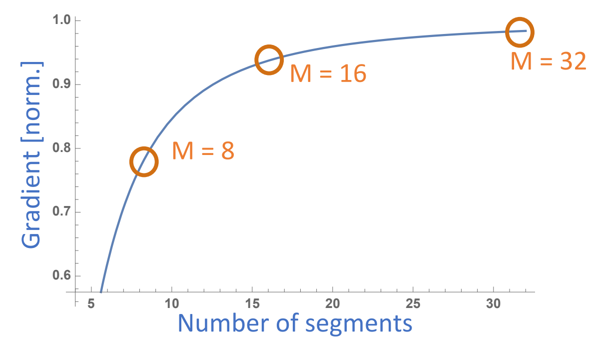


Halbach array



$$B' = 2B_r K\left(\frac{1}{r_i} - \frac{1}{r_o}\right)$$

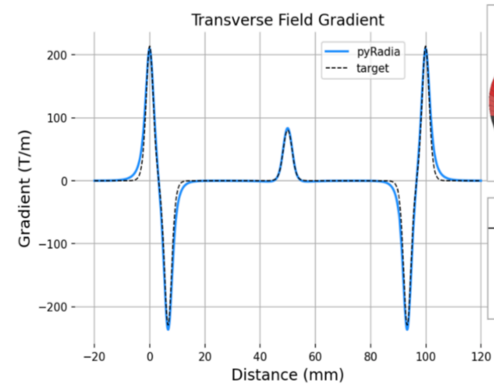
$$K = \frac{M}{2\pi}\cos^2\left(\frac{\pi}{M}\right)\sin\left(\frac{2\pi}{M}\right)$$

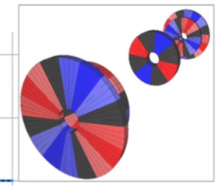


Simulations

- Quintuplet Configuration for UEM
  - Work with BNL UEM group
  - Target: nm resolution
    - Depends on beam parameters (energy spread, emittance, etc.)
  - Symmetric design
- Genetic optimizer algorithms
  - PMQ constructor
  - Radia code (python) with MOGA
  - Particle tracking (Elegant and GPT)
  - Account for fabrication capability, material variances
  - Run >20k cases for tolerance study– optimal solution for high resolution

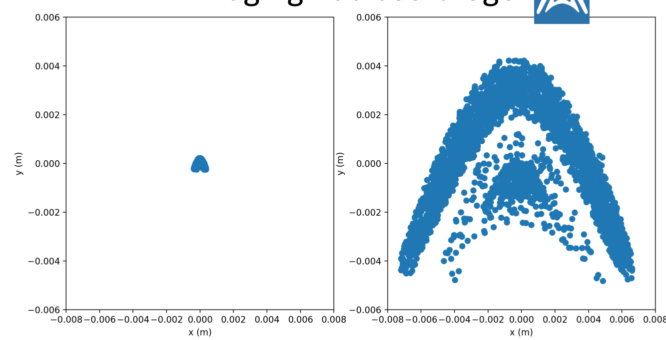
Field gradient for complete quintuplet





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

Imaging Radiasoft logo

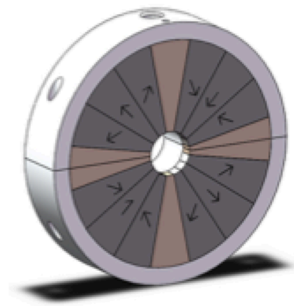


at sample

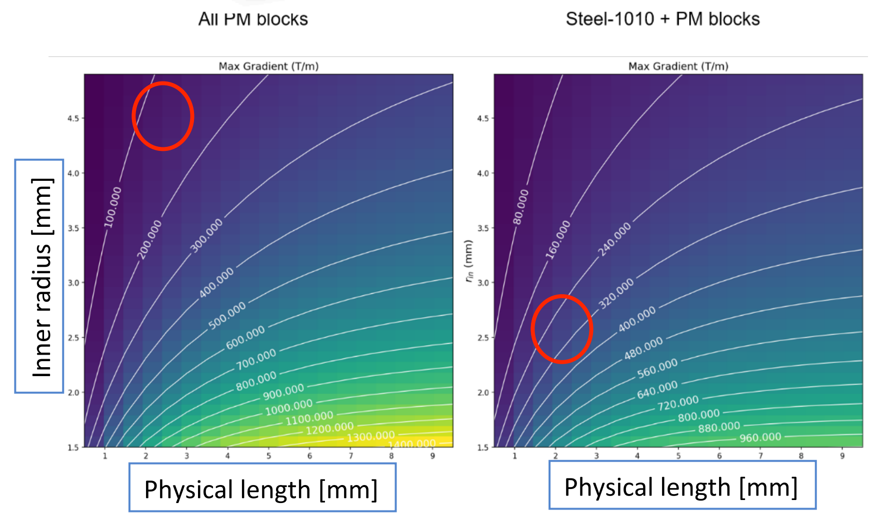
at screen

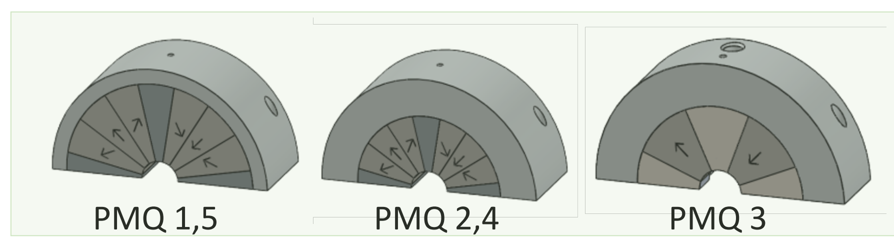
Engineering

- PMQ design
  - Gradient limited by r_i in original design (larger beampipe)
  - Smaller r_i needed for target B'
  - r_i=2.5mm with 2mm beampipe
  - Requires “splittable” design
    - Steel wedge inserts
  - Compatible with future UEM source
- Able to achieve the target gradient with steel wedges
  - Varying r_{outer} to get B'



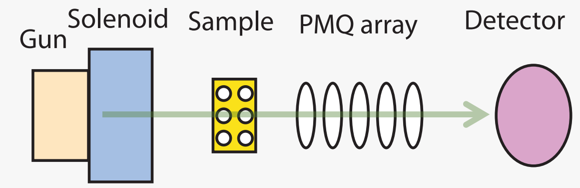
Hybrid PMQ
w/ steel inserts



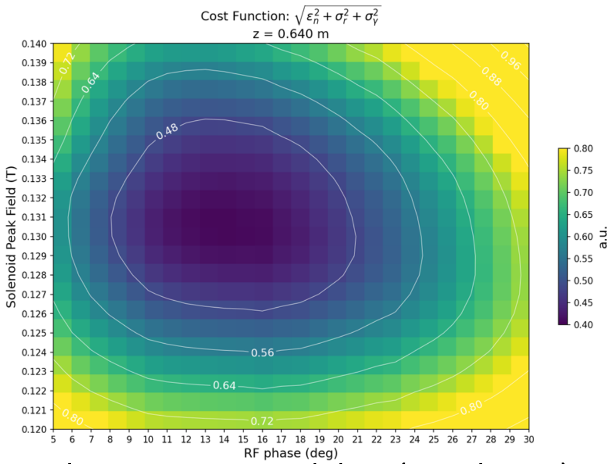


Proposed Experiment

- Simplify to isolate and characterize lens
  - Solenoid lens, target, quintuplet lens, detector
  - “device under test” with calibrated target
- Modeled UED photoinjector performance + transport
  - Optimize beam to fit pipe, and produce image on screen
  - Q=10 pC, ε_N=0.5µm, σ_γ= 3E-3, σ_r=60µm @ z=.64m
  - Space charge forces considered

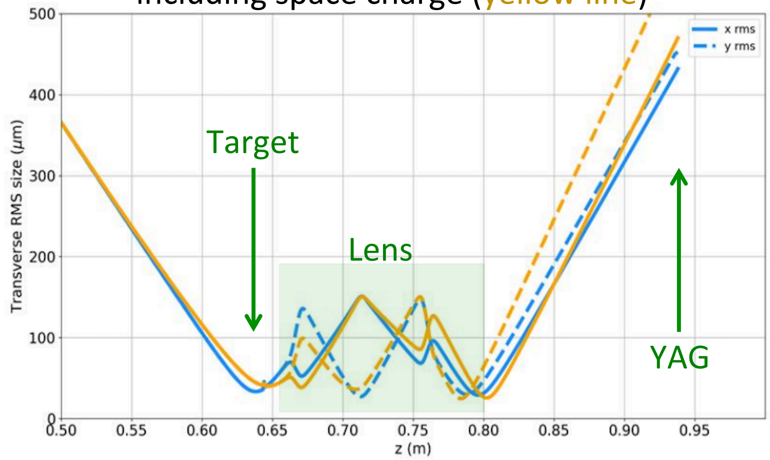


Simple sketch of beamline configuration



Photoinjector modeling (simulation)

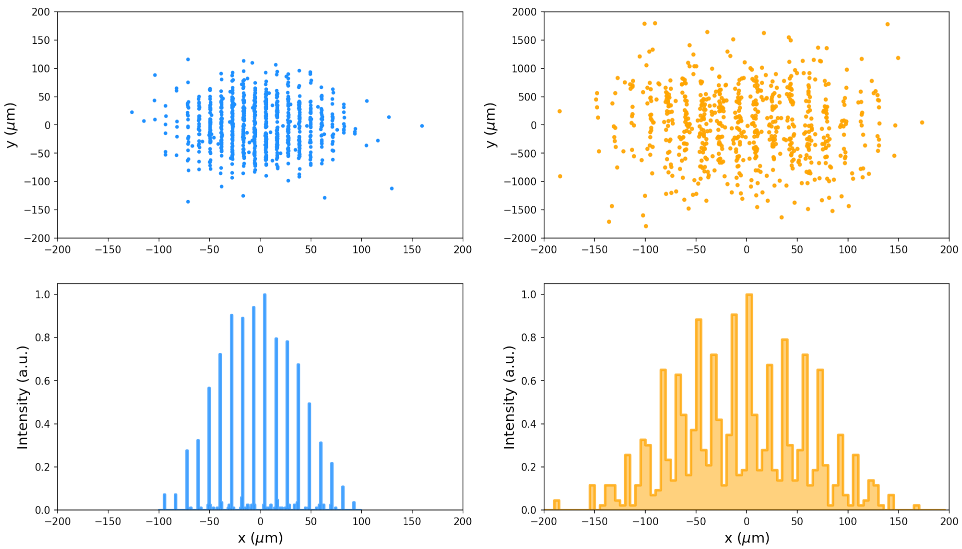
Spot size through beamline (simulation) including space charge (yellow line)



Observables

- Target shadow is imaged on YAG screen
  - 20cm away from last magnet
- Possible targets:
  - Fixed 1µm and 25µm slits
  - “v-shape” on actuator for variability
  - Gridlines (x,y simultaneously), curvature gives info on aberrations
- Note: operating at lower charge may require more sensitive scintillator (YAG)
- Note: need to move screen closer than current location

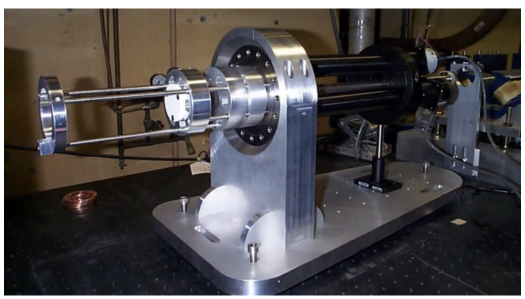
Simulation of 1µm slitted array (Tungsten)



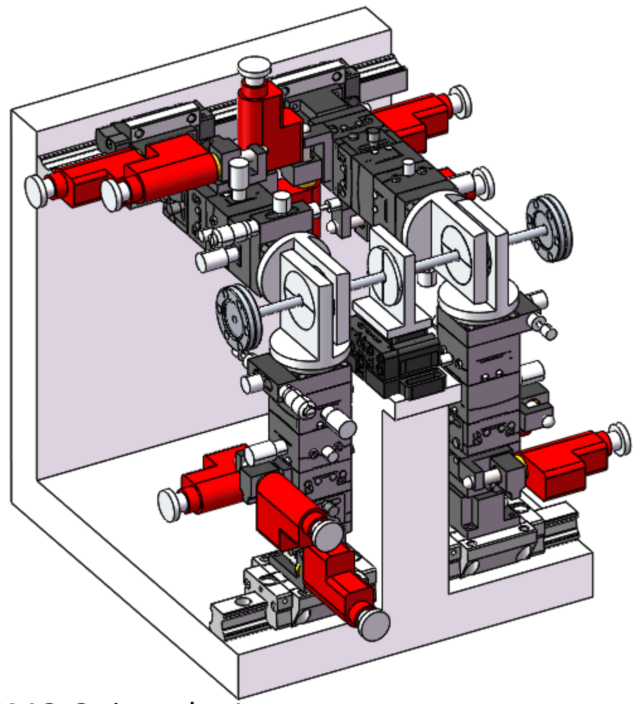
Beam distribution at target   Beam distribution at screen

Beamline integration

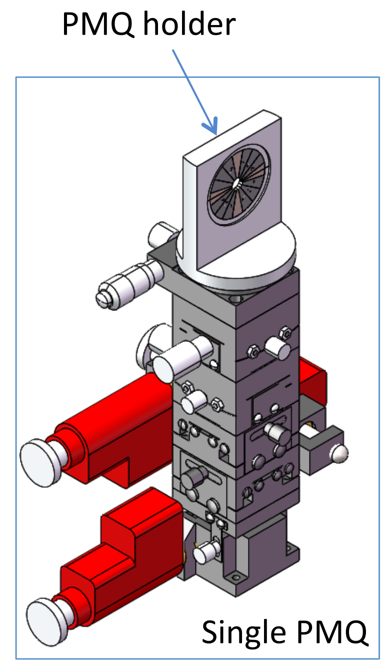
- "Drop-in" system
  - PMQ outside vacuum
  - Beam pipe 2mm radius
  - CF flange for mating
- Singular stage on stand
  - Macro alignment
- PMQs pre-aligned on bench
  - Piezo-motors for fine alignment
  - Remote control of drift lengths



UCLA expt with movable PMQ triplet



PMQ Quintuplet Lens
7.3" (18.5cm) flange-to-flange
7 lbs as shown + 9lbs strongback



5 degrees of freedom
Only z-translation for expt

Timeline

• Assemble PMQ Quintuplet
  • Measure, align quintuplet
  • Reiterate simulations with measured fields
  • Select target
	Today (t_0)
	(18 wks)

• Ship to BNL • System shakeout, re-align on bench	March 30, 2021 (2 wks)
• Install lens and target • reconfigure beamline (YAG + CCD)	April 16, 2021 (1 wk)
• Run experiment • Analyze data + report	April 24, 2021 (2wks)

Summary

- This first proposal aims to characterize the lens with a simplified configuration at the UED line
- Developed full model of UED beamline
  - Full implementation of 3D magnetostatic field maps of PMQs
  - Gun fields, solenoid fields, 3D space charge
- Directly adaptable to UEM project (with dual projector lenses)

Acknowledgements: T. Campese, Y. Chen, I. Gadjev, M. Ruelas (RadiaBeam), C. Hall (RadiaSoft),
M. Fedurin, K. Kusche, X. Yang, Y. Zhu (BNL)
DOE SBIR# DE-SC0018562

Special Equipment Requirements and Hazards

- Indicate whether your experiment requires UED or UEM beams
  - This project is proposed for the UED beamline, but is adaptable to the UEM line as well
- User Sample and Setup
  - Please indicate any special equipment that you expect to need bolometer/interferometer setup etc.:
  - Requires moving existing CCD, and replacing phosphor screen with YAG
- Pump Laser Requirements
  - Please note any special pump laser requirements here: N/A
- Hazards & Special Installation Requirements
  - Large installation (chamber, insertion device, etc.):
    - Installation of PMQ quintuplet, with dedicated stage; beam-pipe uses CF flanges for compatibility to existing beamline
  - Cryogens: N/A
  - Introducing new magnetic elements:
    - New PMQ quintuplet (max gradient 230T/m confined to 2mm radius)
  - Introducing new materials into the beam path:
    - Tungsten slit or grid as a calibration target
  - Any other foreseeable beam line modifications:
    - change CCD location, replace phosphor with YAG

Experimental Time Request

CY2021 Time Request

Capability	Setup Hours	Running Hours
UED Facility	40	80

Time Estimate for Remaining Years of Experiment (including CY2021)

Capability	Setup Hours	Running Hours
UED Facility	40	80