The design of a Permanent Magnet Quadrupole Lens Focusing System for an alpha-irradiator

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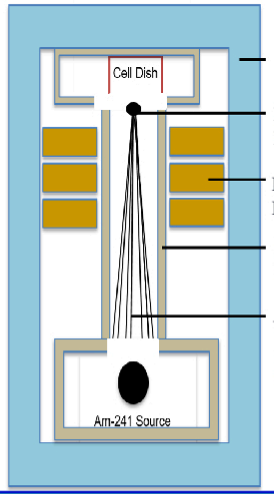
INTRODUCTION

Radiation damage to DNA is considered playing a pivotal role in the determination of the final radiobiological effect. Understanding the fundamental mechanism behind the radiation response at the sub/cellular level is then of critical importance, which will rely heavily on the advancement of theoretical, experimental and computational techniques. To perform advanced measurement of the radiation response at the sub/cellular level, a facility that can provide radiation beams under well controlled irradiation conditions is required. However, in the state-of-the-art micro/nano beam facilities, the reliance of accelerators to produce energetic ions (starting from several MeV/nucleon) limits the replication of beam focusing and control infrastructures. In this work, we proposed to build and optimize a focusing lens system to focus MeV alpha particles generated from Am-241 radiation source. The long-term goal is to build an easy-to-adopt, compact and cost-effective irradiation facility with controlled beam conditions for radiobiology experimental study at the sub/cellular level.

AIM

:We want to design a focusing lens to enable controlled alpha-irradiation study in an easy-to-assemble, compact and cost-effective way – starting with permanent magnet because of the following reasons

- Focusing lens is useful for:
  - ✓ Increases dose rate
  - ✓ Filter out Alpha particles from Gamma
  - ✓ Study bystander effect effectively.



METHOD

COMSOL Multiphysics, a finite element analysis solver, has been used for the design and optimization of the lens assembly. For an initial attempt, we chose to use the electromagnetic focusing lens made up of permanent magnets. AC/DC module from COMSOL was primarily used to generate the geometry for the lens, compute the magnetic field and optimize the lens configuration. The Particle Tracing module was responsible to observe the focusing effects of the lens and for the ray tracing of the alpha particles, based on the results of which, we could adjust the lens geometry or magnetic strength to further optimize the performance of the entire system.

To make the simulated system machinable, we have considered constraints from the following six aspects in our practice. They are: 1) the constraints for the angular divergence of the input beam, 2) the beam energy spread out after passing through a practical vacuum system, 3) the aperture constraints from the vacuum pipe and shielding, 4) the commercial availability of the size and magnetization for the permanent magnets, 5) the assembly capability of the university machine shop for the ion and magnet subsystem and 6) the constraints for the total length of the entire system. .

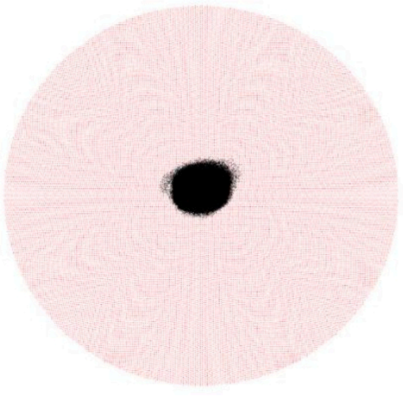
RESULTS

Input beam conditions: the initial beam from the Am-241 source is composed of both alpha particles and gamma rays. 85% of the alpha has an energy of 5.486 MeV while the gamma rays have an energy of 59.54 keV. Our Geant4 based Monte Carlo simulation showed that under a medium vacuum condition of 1E-6 atm, a narrow energy spread out ranging from 4.5 to 4.7 Mev with the peak intensity at 4.604 MeV can be attained for the input alpha beams, assuming the initial beam is isotropic, by applying two apertures of radius 5 and 0.5 mm in addition to an interval of 1 m, we could obtain an alpha beam with a diameter of 1 mm and an angular divergence of 1 mrad, which is then taken as input in the focusing lens simulation and optimization.

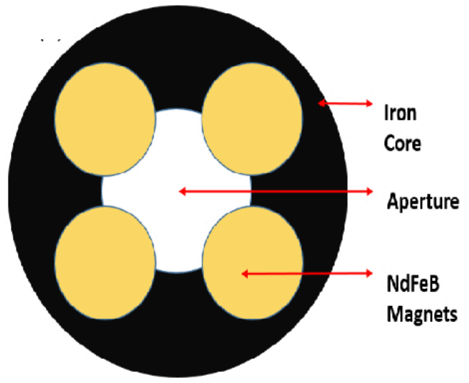
Other constraints: To form the required vacuum, the stainless vacuum pipe is required to be at least 6.084 mm in thickness. Considering the gamma irradiation, we will add 1 mm lead out of the stainless pipe, plus the beam space of 4 mm, we will need an aperture with 11.084 mm in diameter. The commercially available and machine shop workable magnet is found to be of cylindrical shape, with a maximum length, and width of 50.8 and 25.4 mm. For which, the maximum and minimum magnetization are of 1.48 and 1.18, respectively.

The optimized cylindrical permanent Magnet Quadrupole Focusing System: The lens consists of 3 pairs of cylindrical quadrupole magnets separated by drift spaces The diameter/aperture ratio was chosen to be 1.147, which is the most optimal ratio[1] to get the best focusing strength possible The magnets used in the simulations are NdFeB magnets which are magnetized through their lengths. All magnets have the same radii of 7.2835 mm. The second and the third magnet are of same length and strength of 36.4 mm and 1.48 Tesla (Grade N52 which is the strongest industrial grade). The first lens is 18.4 mm in length and 1.18 Tesla in strength (Grade N35 which is the weakest industrial grade). The entire magnet assembly is held together by an iron core which is also responsible to increase the overall magnetic field gradient. The input particles in the lens assembly consist of 4.604 MeV alpha particles which is the average energy from the Am-241 source after a commonly used 2 micron thin gold layer. The particles enter with a divergence angle of 0.001 rad after travelling through a pair of collimators with an interval of 1 m. The entire lens assembly is 244 mm in length, as compact and easy-to-install.

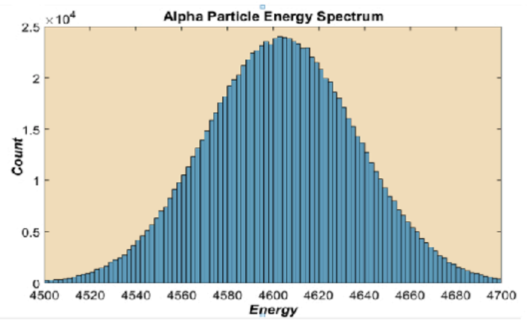
The de-magnification factor for the lens is~7.5) at the object aperture location with a working length of 51 mm Study suggests that taking into account the magnetization and length aberration the lens produces a constant de-magnification in the range of 4.5-7.5.



The focused particles are represented with black dots with the background red particles representing the initial input beam



The front view for the lens assembly showing the lens aperture and the NdFeB magnets



Energy distribution for alpha particles after 2μm of gold foil

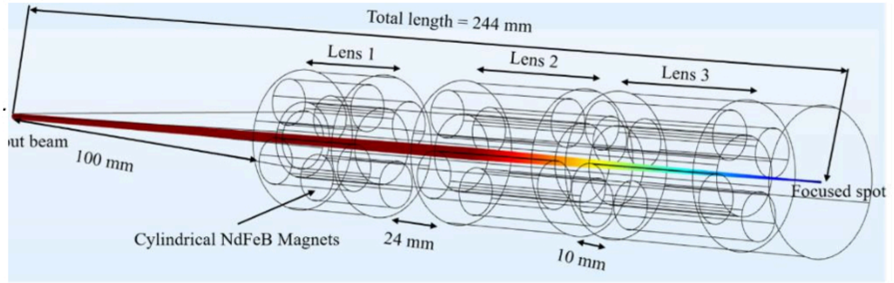
Parameters	Constraint	Optimized	Within Constraint
L Total (mm)	304.8	244	✓
Max. D (mm)	25.4	13.68	✓
Max. L (mm)	50.8	45	✓
Max. M (Tesla)	1.48	1.45	✓
Min. M (Tesla)	1.18	1.18	✓
Min. A (mm)	11.084	12.70	✓

Table 1: PMQ values along with the constraints for each parameter and the final optimized value.

DISCUSSION

Lens has a de-magnification of (7*10) for 1mm input beam with 1 mil. radian input divergence.

The lens has a 60 mm Working Distance, giving flexibility to add beam scanning instruments.



CONCLUSIONS

We demonstrated the achievability of the concept of forming focusing beams from natural radioactive source by the design and optimization of a magnetic quadrupole triplet for an alpha irradiator. All the parameters were optimized in accordance to make the lens system a very practical, easy to build focusing system. The future work will be focused on improving the focusing strength of the system with more powerful lens, for example, electrostatic/electromagnetic lens, etc..

- ✓ De-mag of (7*10) was achieved for 1 mm input beam with 1E-3 rad. Divergence.
- ✓ De-mag can be increased to (14*29) by increasing input beam to 3 mm.

ACKNOWLEDGEMENTS

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REFERENCES

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2. H. Wollnik, *Optics of Charged Particle Optics* (Academic Press Inc., London, 1988).

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