Study of Quantum Efficiency Enhancement in Different Mie-type Nanostructured NEA GaAs Photocathodes

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Abstract:

The interaction of 500-800 nm radiation with Mie-type nanostructured GaAs of different shapes (truncated nanocone, nanopyramid and nano-square columns) has been studied using the Lumerical's Finite Difference Time Domain (FDTD) and CHARGE tool. The motivation is to design an optimized structure for Negative Electron Affinity (NEA) GaAs photocathode which supports Mie-type resonance to maximize the quantum efficiency (QE) in 700-800 nm wavebands for generation of polarized electrons. At resonance wavelengths these reported structures present a very small reflectance as low as 1%, resulting in much higher QE. The simulated QE around 780 nm shows much strong enhancement up to 27% due to the shifting of resonance towards the longer wavelength compared with the results from previously reported Mie-type NEA nanopillar array GaAs (< 15%) and flat NEA GaAs wafer (~13%) photocathodes. The field profile distribution shows that most of the photoelectrons are generated within the nanostructures at a location ~100 nm away from the top and side emission surfaces, where the transport of most of the photoexcited electrons to the emission surface occur and contribute to the emitted electrons. The field profile distribution along with the field lines also shows the excitation of dipole and quadrupole modes within the nanostructures at resonant frequency. The significant increase in the QE of the studied structures around 780 nm indicates that this type of photocathodes could be a very promising candidate needed by high current accelerators such as CEBAF at Jefferson Lab and the future Electron Ion Collider.

- QE enhancement study
- 3 different nano-structures: nano-square column array (NSCA), nanocone array (NCA), and nanopyramid array (NPyA)
- Simulation tool: Lumerical FDTD & CHARGE

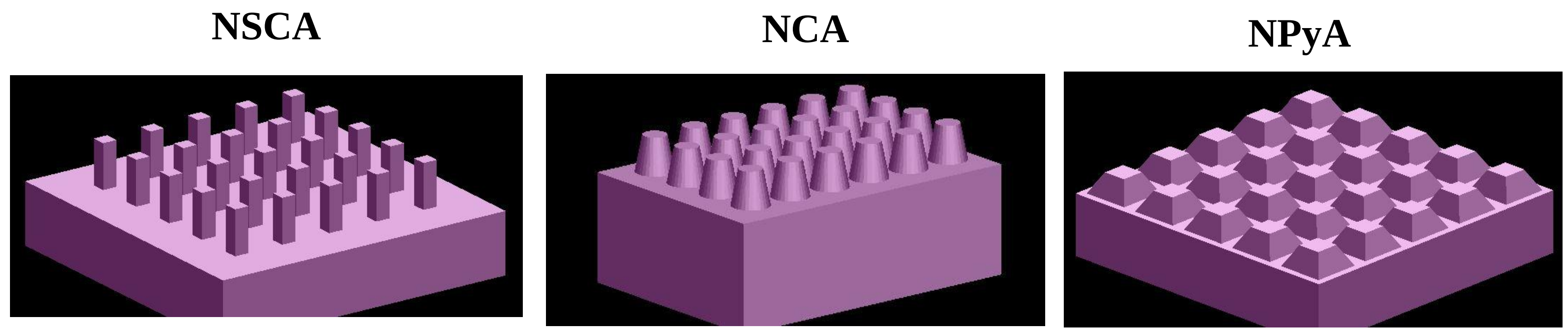

Figure 1: Different types of NEA nanostructured GaAs photocathodes.

1. Negative Electron Affinity (NEA) Nano-Square Column Array (NSCA) GaAs Photocathode:

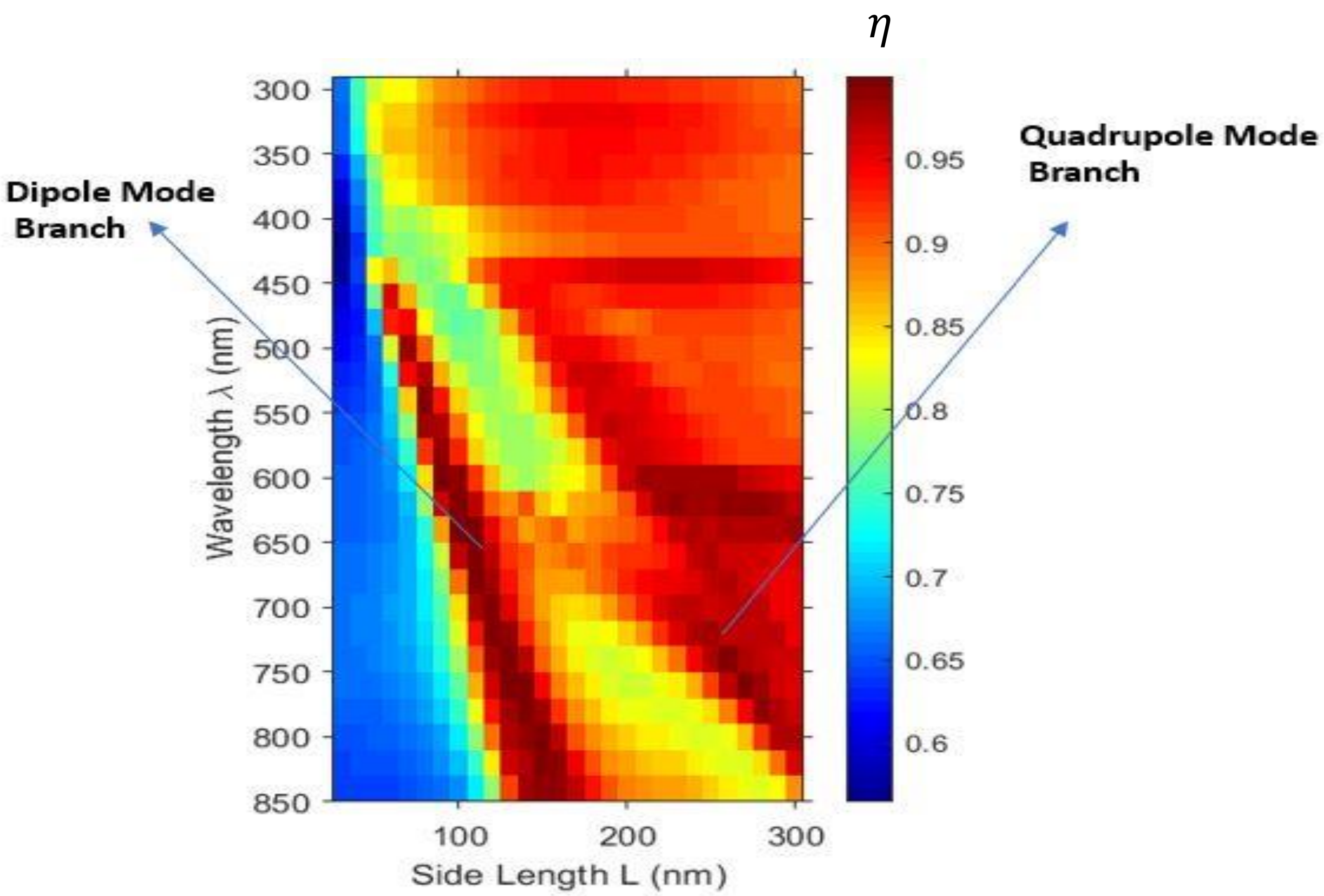

Figure 2: Absorptance spectra vs. side-length variation of NSCA.

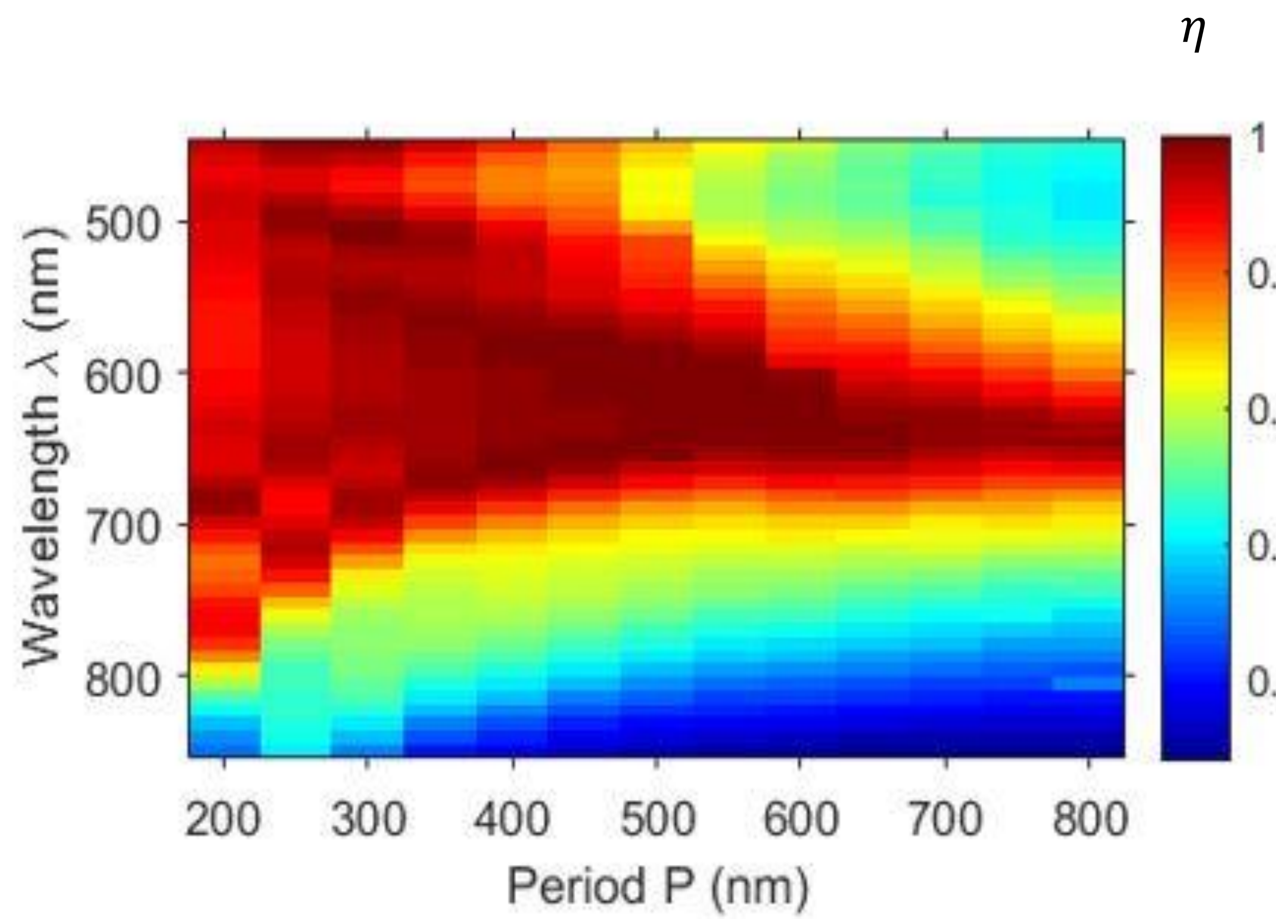

Figure 3: Absorptance spectra for period variation of NSCA structure

- ➢ Nano-square column's side-length is varied between 30-300nm with height and period fixed at 1200 nm and 600 nm respectively,
- ➢ Two branches with absorptance exceeding 0.95 are observed: magnetic/electric dipole (MD/ED) branch and magnetic/electric quadrupole (MQ/EQ) branch.

- ➢ NSCA's period is varied between 200-800nm with height and side-length fixed at 1200 nm and 100 nm respectively,
- ➢ Peak region with absorptance >0.95 becomes narrower with increase of period,
- ➢ At shorter period, the reflected light is absorbed by the side-walls of neighboring columns.

1. NEA NSCA GaAs Photocathode:

Three different NSCA structures (A1, A2, and A3) have been calculated:

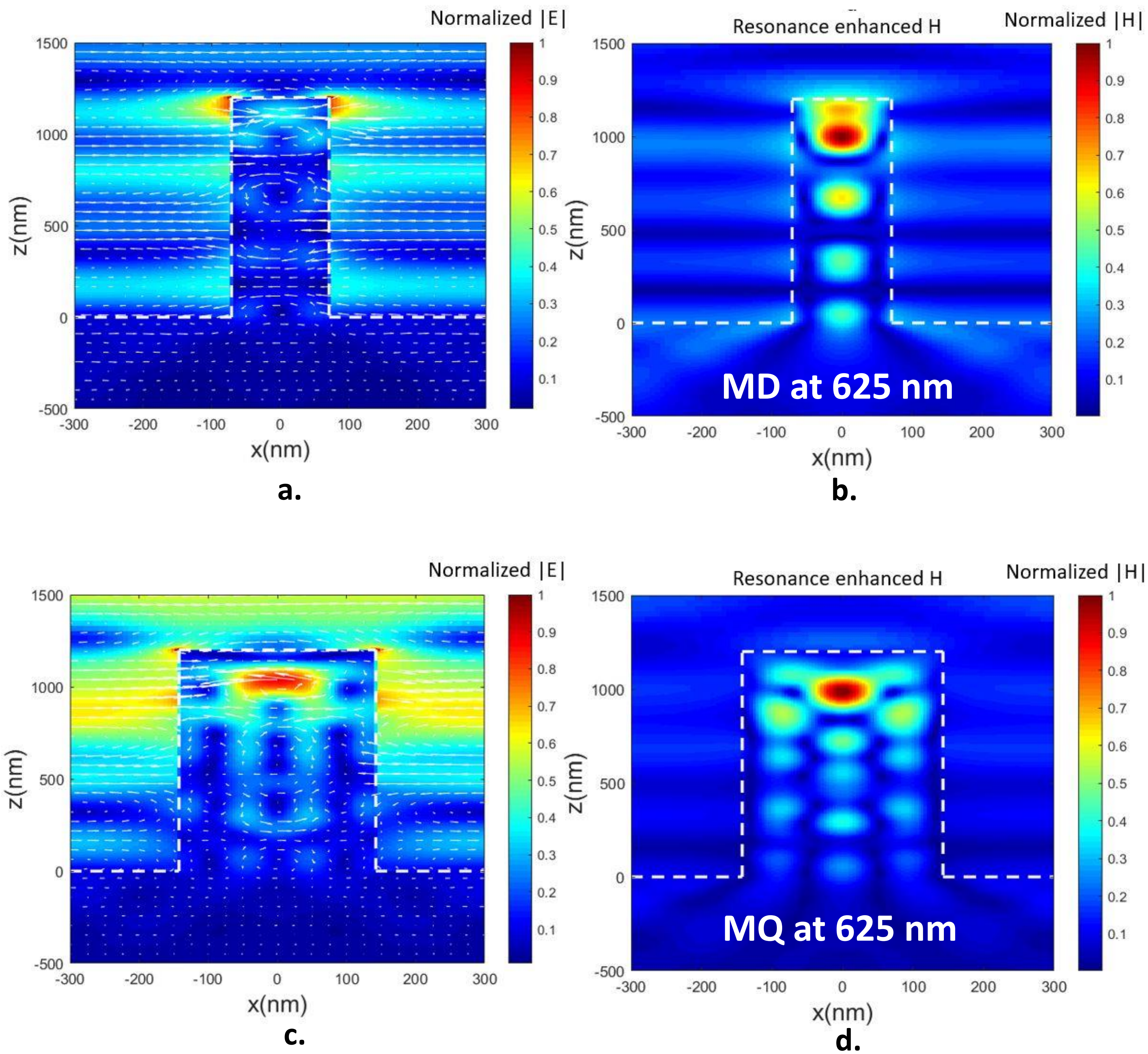

Figure 5: Electric field profile distribution along with field lines (white arrow) showing MD mode excitation for A1 (a-b) , and MQ mode excitation for A2 (c-d) at 625 nm wavelength.

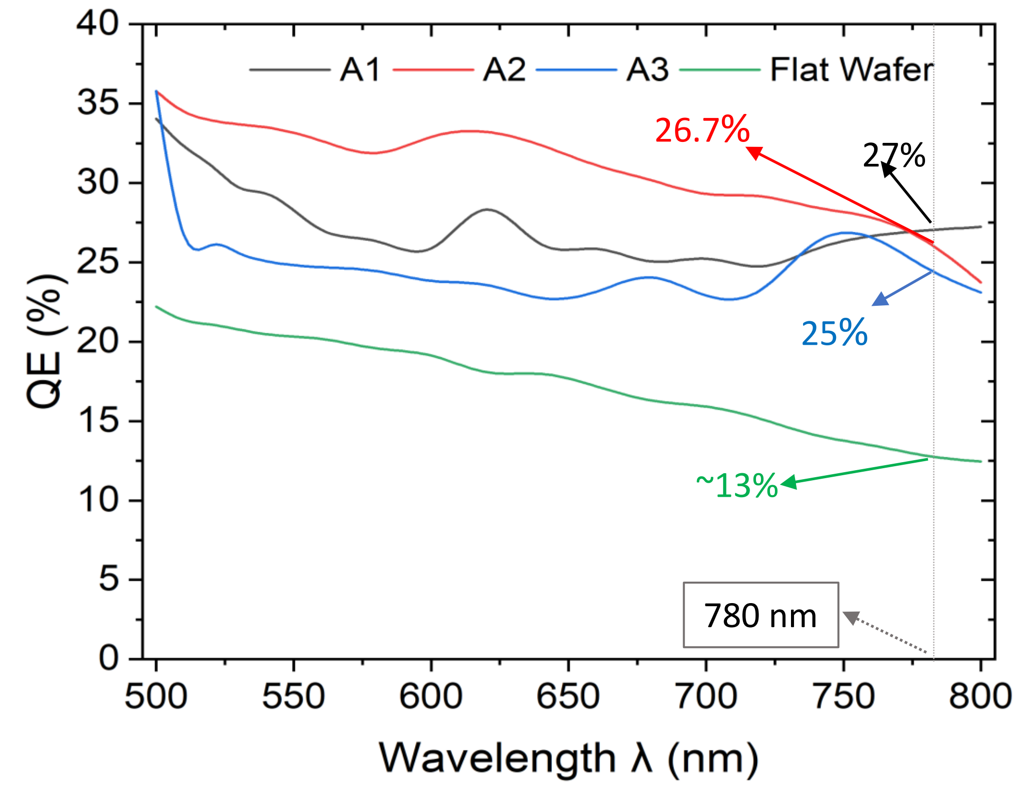

Figure 4: Comparison of QE between different NEA NSCA GaAs and flat wafer GaAs photocathodes.

NSCA	Side-Length (nm)	Height H (nm)	Period (nm)	QE at resonance wavelength
A1	142	1200	600	~28% at 625nm (MD/ED)
A2	285	1200	600	~ 33% at 625 nm (MQ/EQ)
A3	125	1200	800	~27% at 750 nm (MD/ED)

- A1 and A2 have MD/ED and MQ/EQ mode excitation at 625 nm, resulting in 28% and 33% QE respectively.
- A1 exhibits QE of 27% at 780 nm (the maximum) due to MD/ED excitation.
- All three structures exhibit overall improvement in QE compared to flat wafer GaAs photocathode [1].

2. Negative Electron Affinity (NEA) Nanocone Array (NCA) GaAs Photocathode:

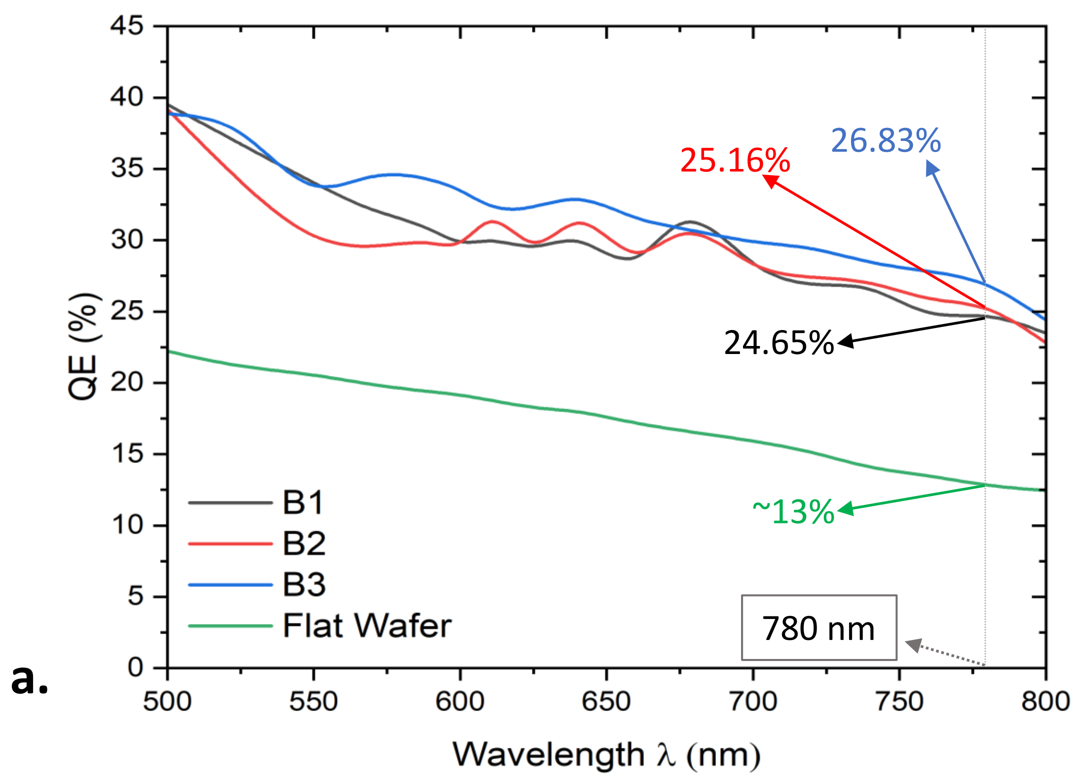

Table: Truncated nanocones with different size and corresponding resonance wavelength:

NCA	Top Diameter	Base Diameter	Height	Period	QE at resonance
B1	150 nm	240 nm	550 nm	300 nm	31.13% at 675 nm (MD/ED)
B2	150 nm	200 nm	550 nm	300 nm	29.15% at 660 nm (MD/ED)
B3	137 nm	182 nm	1400 nm	300 nm	34.22% at 590 nm (MD/ED)

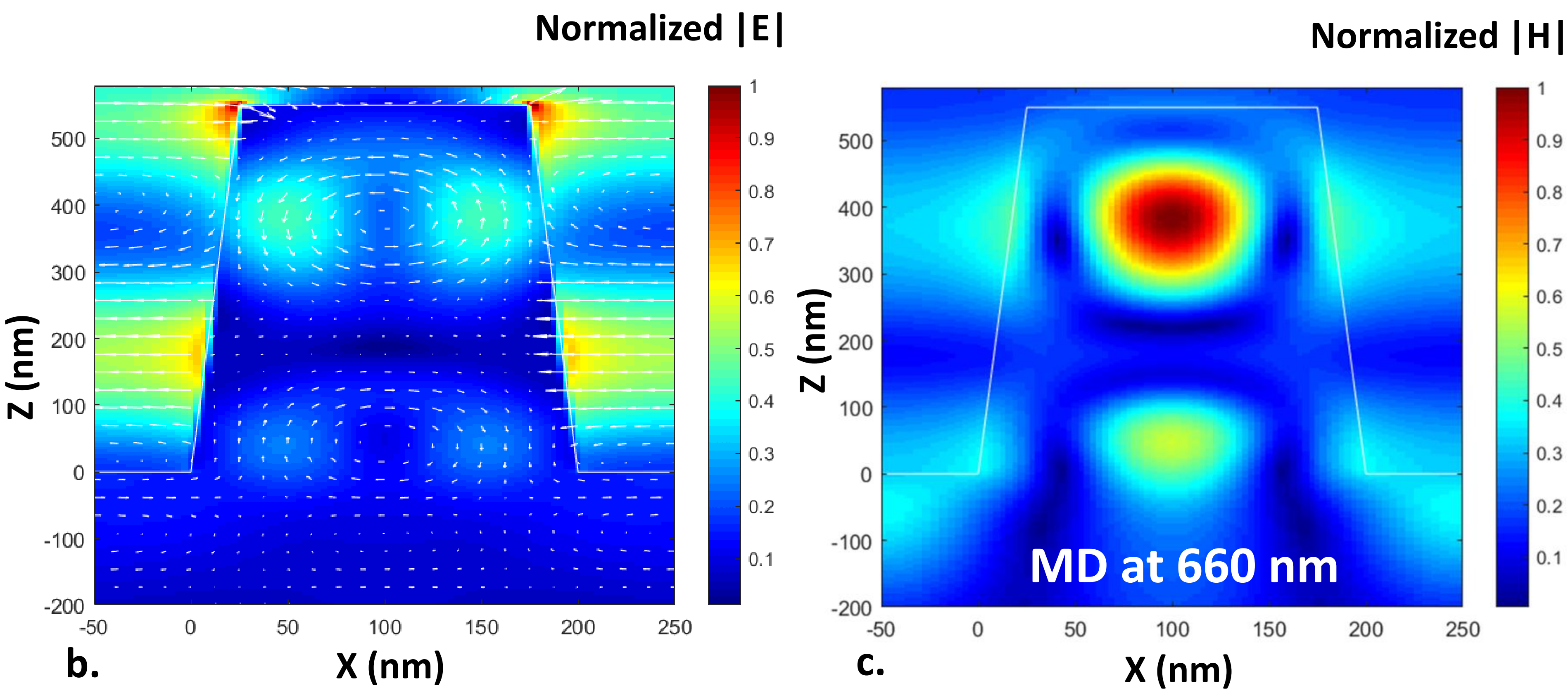

Figure 6: Comparison of QE spectra for different NEA NCA GaAs photocathodes (a), Excitation of MD (b) and resonance enhanced H-field (c) for B2 at 660 nm.

- NCA structures exhibit Mie resonance when light interacts with sub-wavelength sized truncated cones,
- All structures show enhancement in absorption and QE spectra.
- Resonance wavelength shifts toward longer wavelength as base diameter increases,
- B1, B2 and B3 also excites MD/ED mode at 780 nm , enhancing QE significantly compared to flat wafer GaAs [1] and previously reported nanopillar array (NPA) GaAs photocathodes [2].

3. Negative Electron Affinity (NEA) Nanopyramid Array (NPyA) GaAs Photocathode:

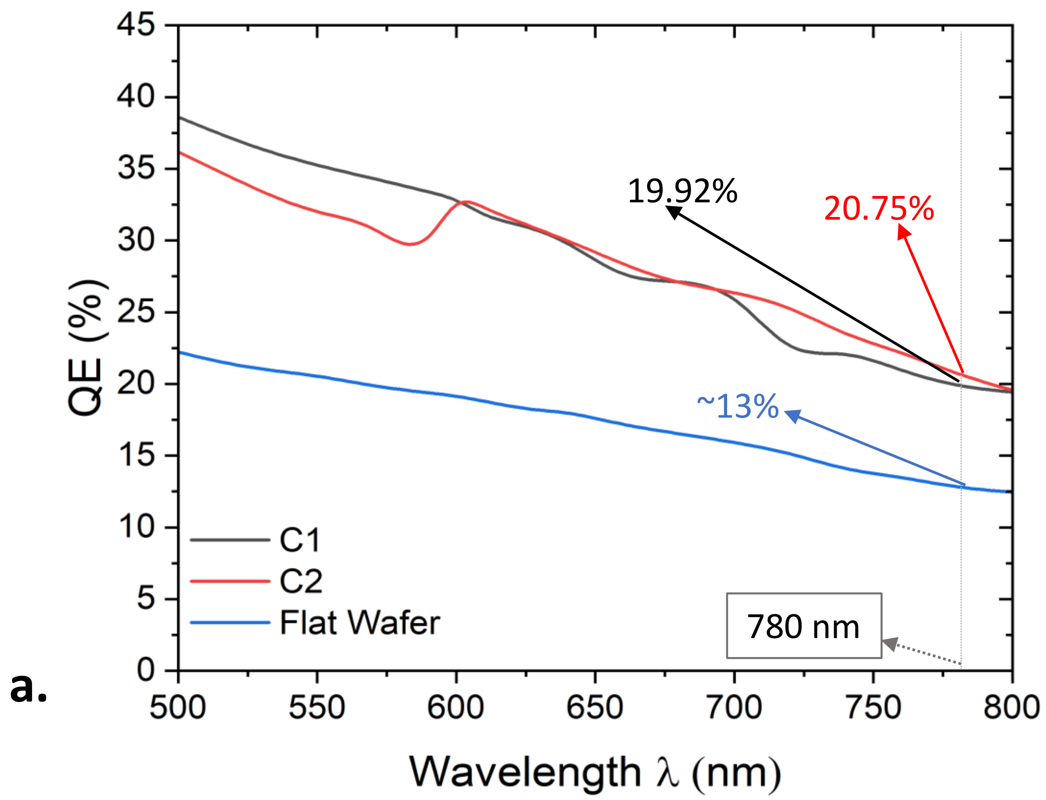

Table: Nanopyramids with different size and corresponding resonance wavelength:

NCA	Top Side-Length	Base Side-Length	Height	Period	QE at resonance
C1	150 nm	300 nm	550 nm	300 nm	31% at 625 nm 21% at 760 nm ~20% at 780 nm
C2	232 nm	464 nm	550 nm	600 nm	32% at 605 nm 26% at 710 nm ~21% at 780 nm

- Unlike NCA and NSCA, co-existence of MD-MQ modes are observed in NPyA as shown in figure 7(b-c), enhancing the light absorption significantly.

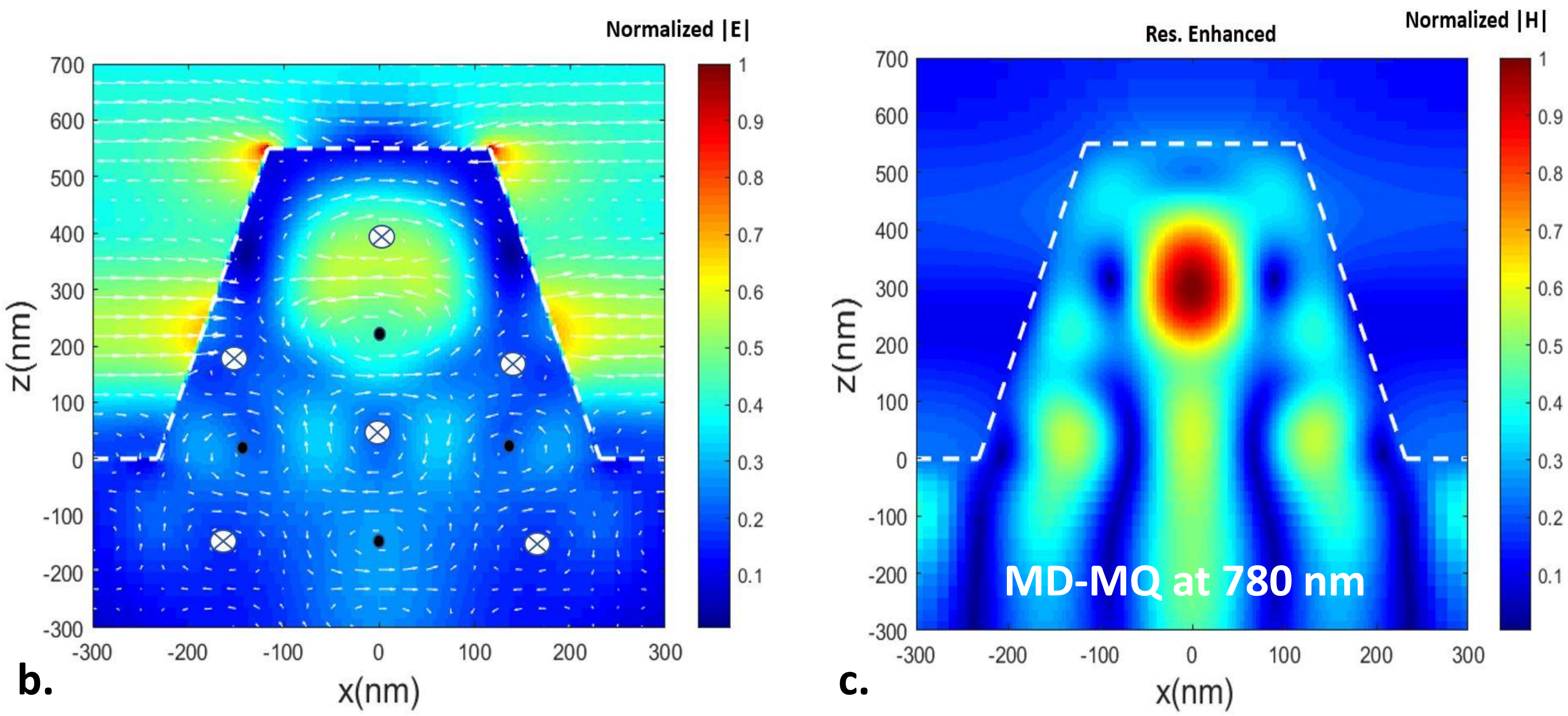

Figure 7: Comparison of QE spectra for different NEA NPyA GaAs photocathodes (a), Coexistence of MD-MQ mode (b) and resonance enhanced H-field (c) for C2 at 780 nm wavelength.

Summary:

- The studied Mie-type nanostructures significantly enhances absorption and hence enhances the QE by the excitation of MD/ED or MQ/EQ modes at resonance wavelengths.
- Overall improvement in QE has been observed compared to the flat wafer GaAs because of enhanced light trapping.
- Among all the studied structures, NSCA and NCA NEA GaAs exhibit maximum QE (~27%) at 780 nm which has made them a promising candidate for electron accelerator at CEBAF, Jefferson Lab.

References:

1. W. Liu, et al., “The effects of ion bombardment on bulk GaAs photocathodes with different surface- cleavage planes,” PRAB **19**(10), 103402 (2016).
2. X. Peng, et al, “Optical-Resonance-Enhanced photoemission from Nanostructured GaAs Photocathodes,” Physical Review Applied 12, (2019).

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