Proton acceleration in thin foils with micro-structured surface

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**also with IoP AS CR in the frame of OPVK project*

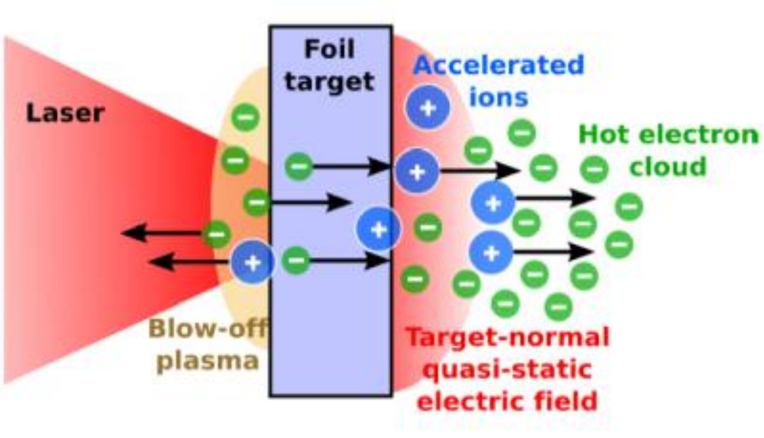
Contents

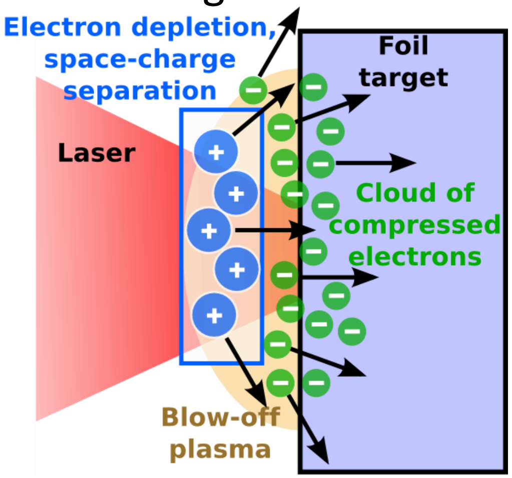
- Basic schemes of ion acceleration by laser
- Possible methods of TNSA enhancement
- Impact of microstructure on the laser irradiated foil side
- Targets with a monolayer of microspheres on thin foil
- Optimization of the microsphere target
- 3D PIC simulations (preliminary)
- Experiment on GIST 100 TW laser
- Experimental proof of proton acceleration enhancement
- Future – 1 PW laser at GIST, Korea
- Conclusions

Ion acceleration by fs laser pulses

- **quasineutral** – acceleration in thin solid foils

  electrons are heated by the laser (**TNSA**) or shifted towards the target interior by ponderomotive force (**RPA**) but not removed from the target





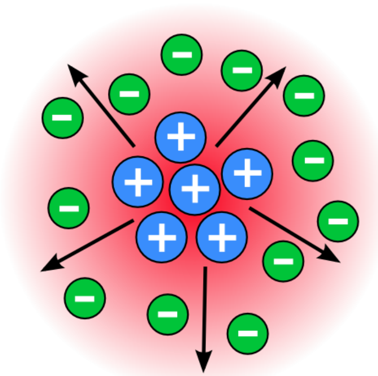
TNSA better suited for present intensities, maximum proton energy $\sim I^{1/2}$

RPA difficult to demostrate at present intensities, maximum proton energy $\sim I^2$

- **non-quasineutral** – acceleration in clusters

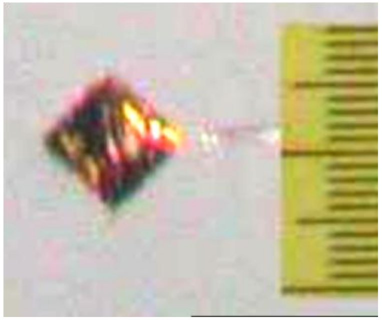
  electrons are partially but rapidly removed from the cluster, making the cluster positively charged

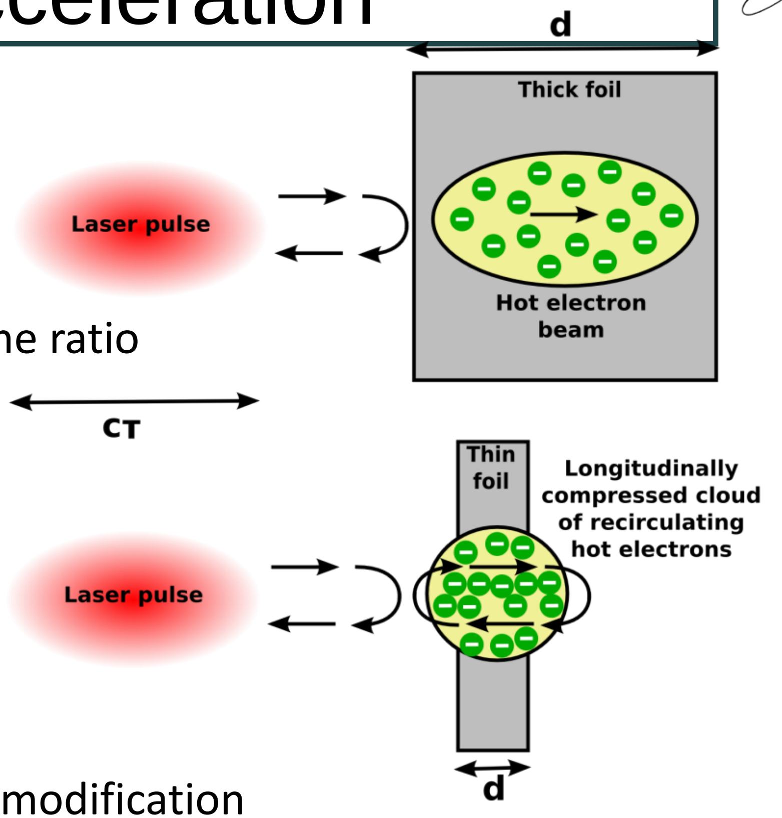
  - small clusters – **Coulomb explosion**
  - larger clusters – Coulomb explosion together with ambipolar (hydrodynamic) expansion



TNSA acceleration

- **Increase TNSA efficiency**
  - thin foils or reduced mass targets – recirculation of hot electrons, important parameter surface to volume ratio





  - absorption efficiency – target surface modification velvet, microspheres, snowflakes etc.

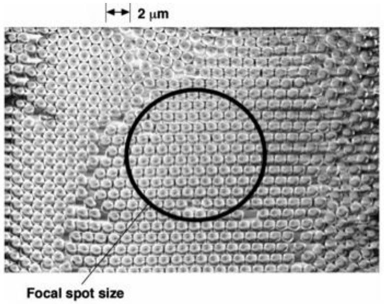


FIG. 1. Scanning electron microscope image of 1 μm diameter polystyrene spheres arrayed on a Cu substrate. The apparent dimples on the spheres are an artifact of the SEM measurement.

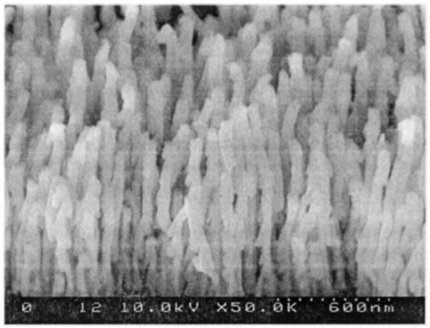
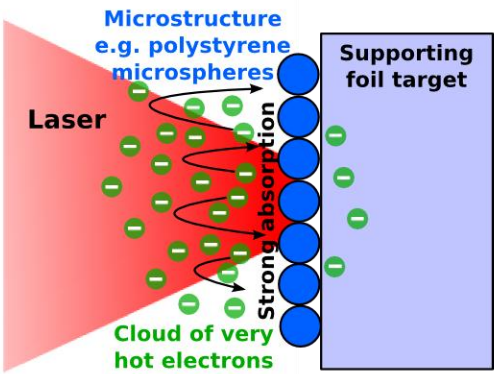


FIG. 1. Scanning electron micrograph of a Ni-nanowire target, showing a structure much like velvet fabric.

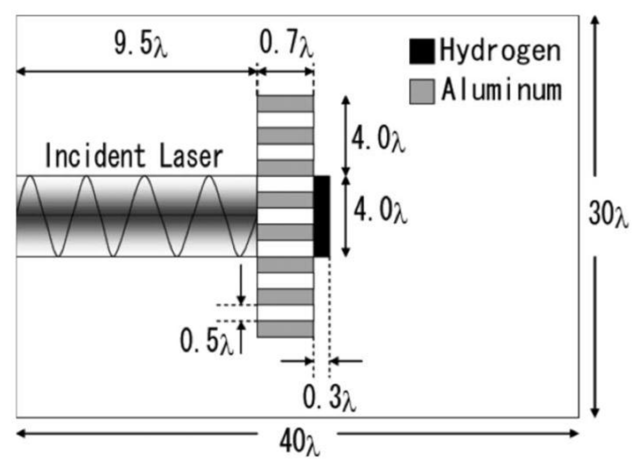


Motivation for surface structure

- Maximum ion energy and conversion efficiency can be increased by decreasing foil thickness and using **high contrast laser pulse** to avoid foil disruption.
- **Absorption of** an ultra-short **prepulse-free** intense laser **pulse on a flat surface** of solid foil **may be low** especially at normal/near-normal incidence.
- Laser **absorption may be boosted by presence of microscopic structures** on the laser irradiated target surface. Influence of microscopic structure on ion acceleration has not been studied previously in experiments.

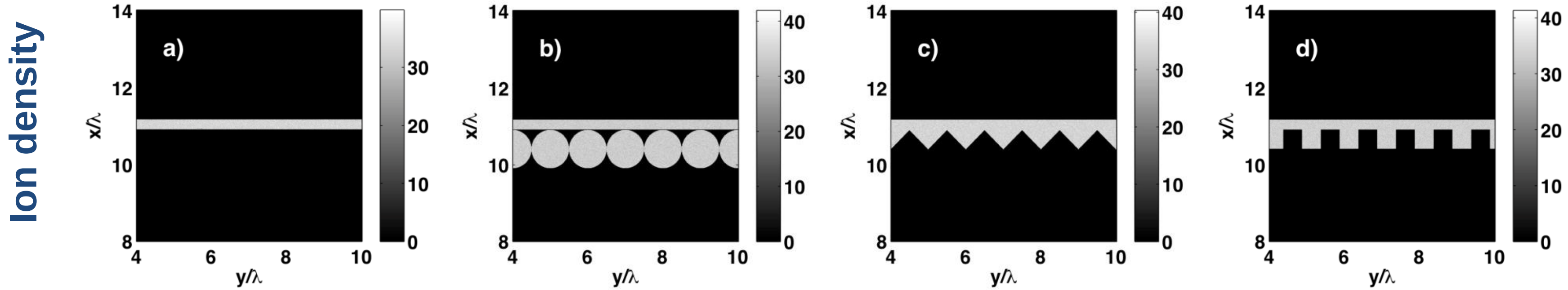
Idea using target structure for ion acceleration

- Idea of using micro-structured targets for ion acceleration comes from Prof. Kawata and his student Nodera (PRE **78**, 046401, 2008)
- **Max. proton energy increased from 3 to 10 MeV** using this multi-hole target, **the efficiency of proton acceleration increased 6 times**.



Influence of surface structure

- The influence of the shape of the surface structure studied in our 2D3V relativistic electromagnetic PIC simulations. O. Klimo et al., New J. Phys. 13, 053028 (2011)
- Target - 200 nm thick foil with or w/o periodic surface structure at the front side, 2 species of ions (homogeneous 1:1 mixture of C4+ and protons).



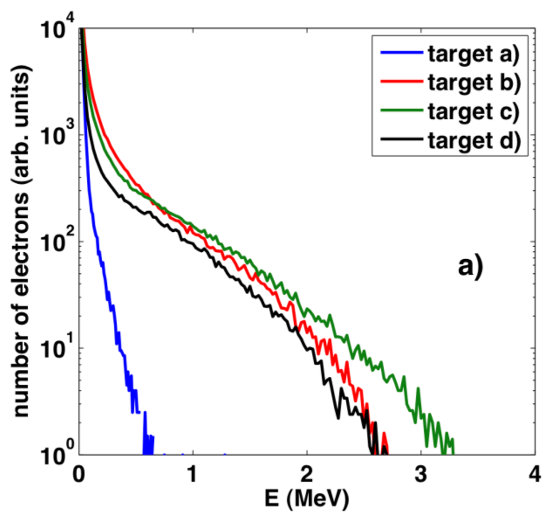
20 fs long laser pulse, λ=800 nm, 2×10^{19} W/cm^2

target	electron temperature	electron divergence	absorption	max. proton energy
a)	0.10 MeV	14.8°	3.8%	0.85 MeV (0.88%)
b)	0.40 MeV	39.7°	55.2%	3.76 MeV (7.3%)
c)	0.42 MeV	41.8°	80.5%	4.85 MeV (11.3%)
d)	0.37 MeV	40.9°	43.9 %	3.73 MeV (5.0%)

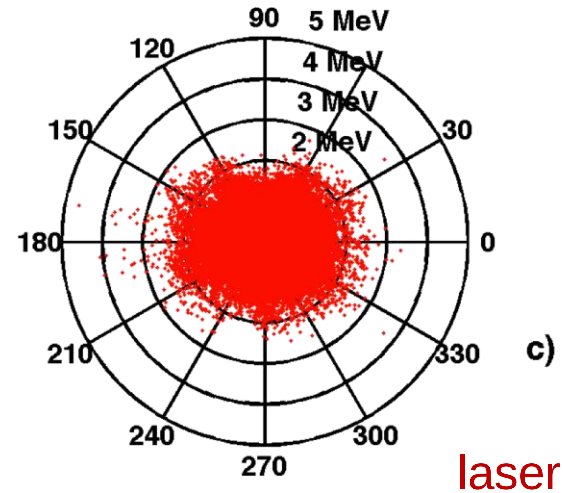
Hot electrons and their distribution

- Flat foil surface**, temperature and number of hot electrons much lower** but hot electron beam is collimated.
- The **structures** on the target surface **cause higher absorption**, but the hot electron beam is very divergent.
- The surface **structures boost laser energy absorption.**
- **No big difference between structure shapes.**

Electron spectra, angular distribution for target B (spheres) and target A (flat foil)

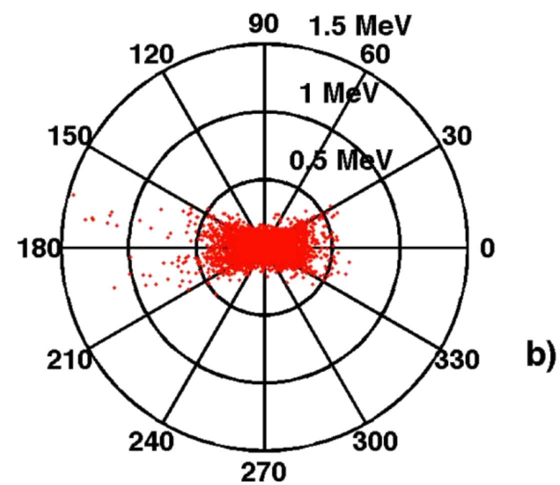


target B



laser

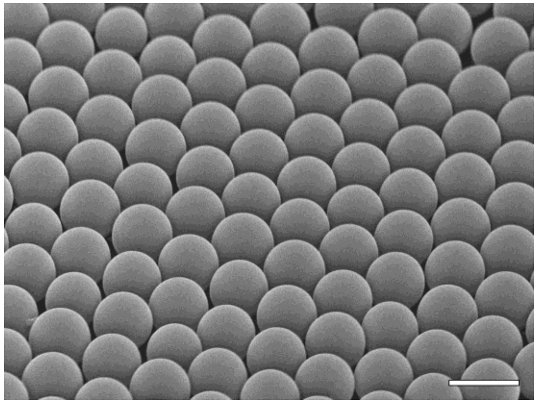
target A

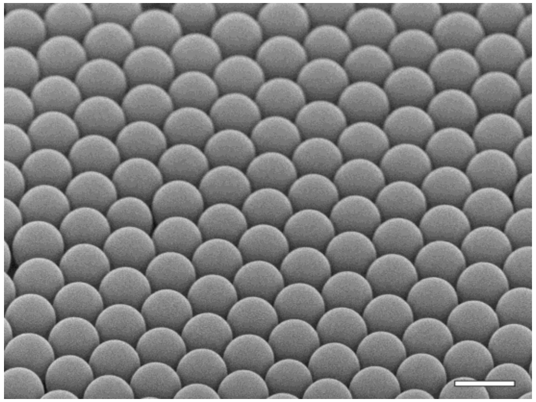


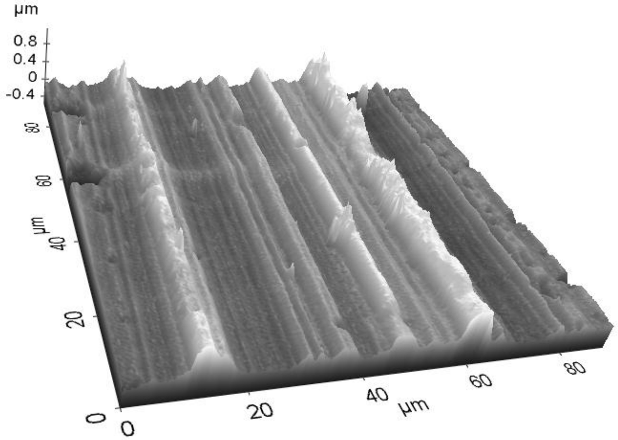
Monolayer of microspheres on foil

- There is **no big difference between structure shapes.**
- We proposed using **thin foil covered by monolayer of closely packed polystyrene spheres** of various size.
- Can be prepared by self-assembly at water/air interface.
- Proposed target are quite **simple for fabrication and optimization**.

SEM images of 900 nm and 530 nm spheres on plastic foil and image of foil

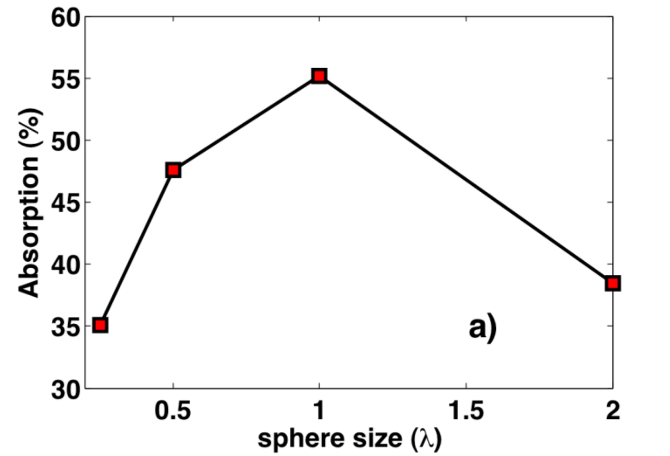




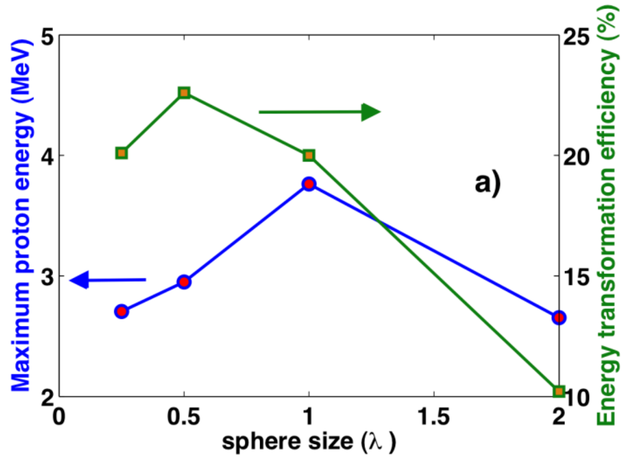


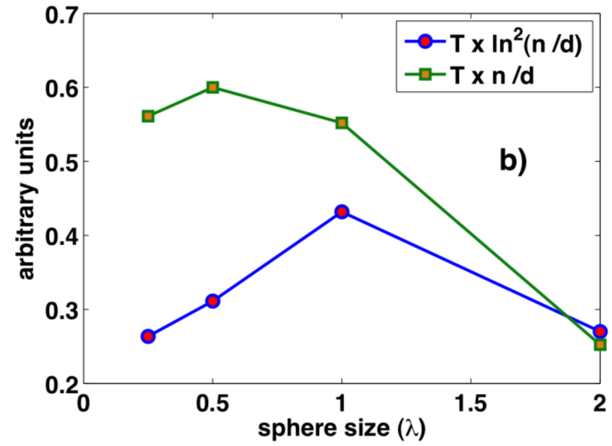
- The AFM image of commercial 2 µm thick Al foil shows irregular grating like structure with variable size of grooves probably due to the fabrication process.
- The groove size is comparable with the Ti:Sapphire wavelength and this grating can significantly influence the results of experiment. $\Rightarrow$ comparison for bulk

Optimization of microsphere size



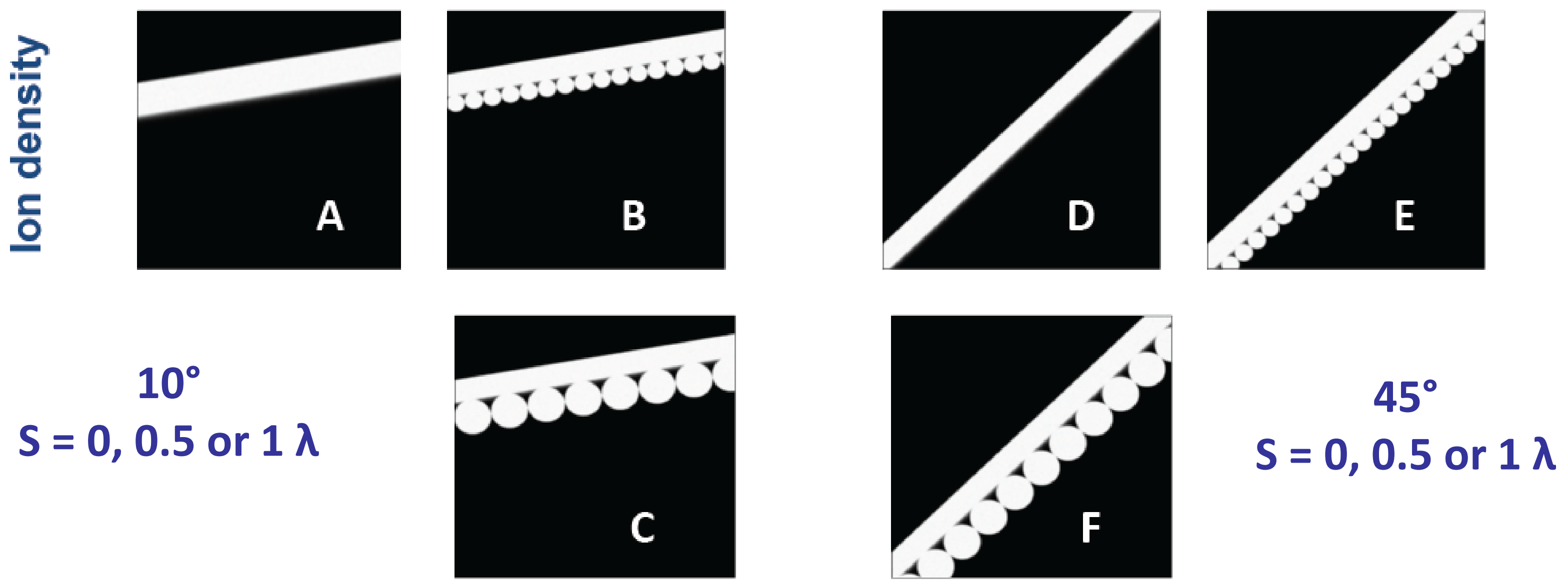
- **Optimum** microsphere **diameter** for laser absorption and maximum proton energy is **close to laser wavelength.**
- According to theory, which does not include hot electron recirculation effects, maximum proton energy scales like $E_{max} \approx T_{hot} \times ln^2(n_{hot})$, while the energy transformation efficiency scales like $\eta \approx T_{hot} \times n_{hot}$.
- The foil thickness is much smaller than the spatial length of the laser pulse ($c\tau$) in our simulations and thus hot electron recirculation is important.
- In this case, n_{hot} must be replaced by n_{hot}/d, where d is the foil thickness.
- Hot electron **recirculation** is more **important for energy transformation efficiency** than for the maximum ion energy.





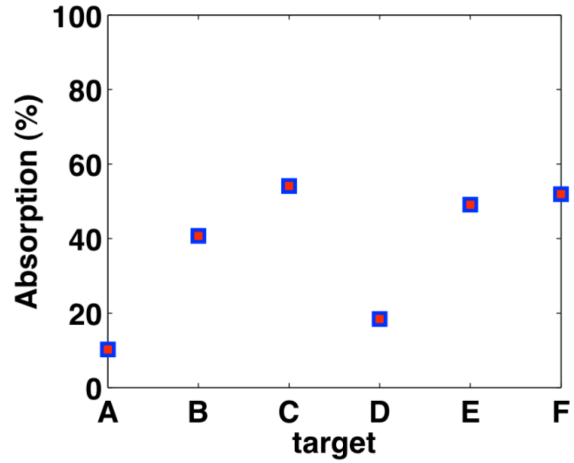
Conditions closer to experiment

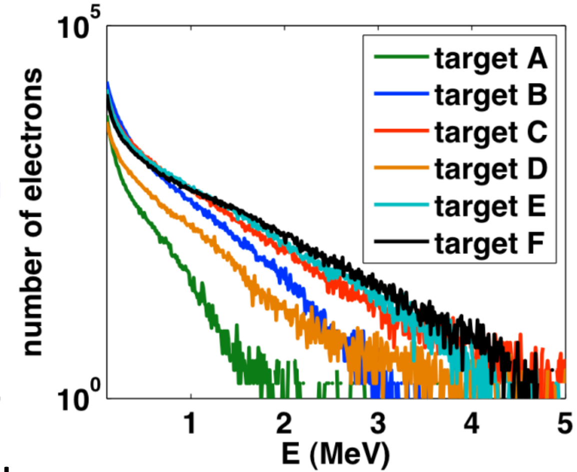
- The foil thickness increased to 0.5 µm - thicker foil can better support the surface structure without being damaged or bent.
- The laser pulse duration increased to 40 fs and the intensity reduced to 10^{19} W/cm^2.
- The laser pulse incidence angle is either 45° or 10° with respect to the target surface normal direction.
- The angle of 10° instead of normal incidence - closer to the experimental practice aiming to avoid strong laser pulse back-reflection.



Laser absorption and electron acceleration

Laser absorption in targets with microspheres attains **60%** and does not strongly depend on the incidence angle or the sphere size in the range 0.5-1λ.

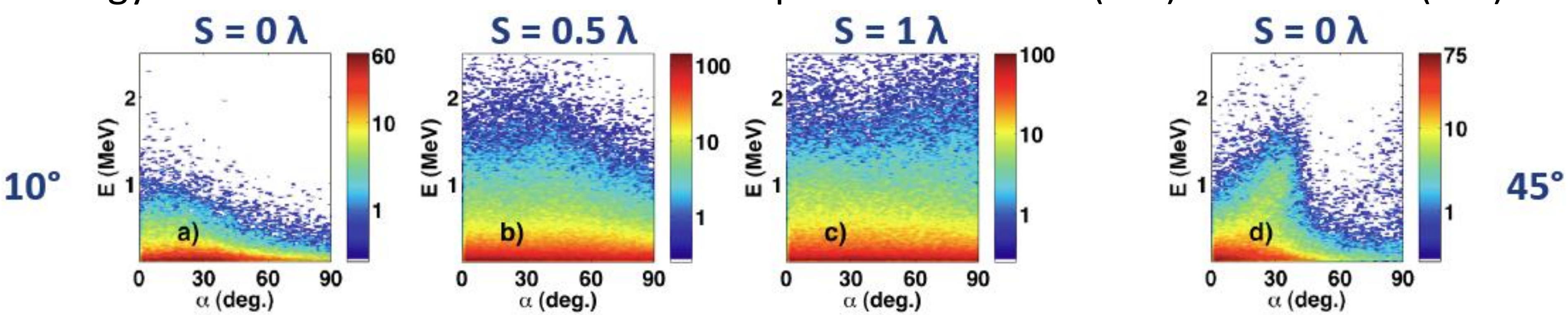




The absorption is less than 20% for raw flat foils and the dependence on incidence angle is much stronger.

The hot electron energy distributions for the target with microspheres B, C, E and F are similar and the hot electron temperature is about 500 keV.

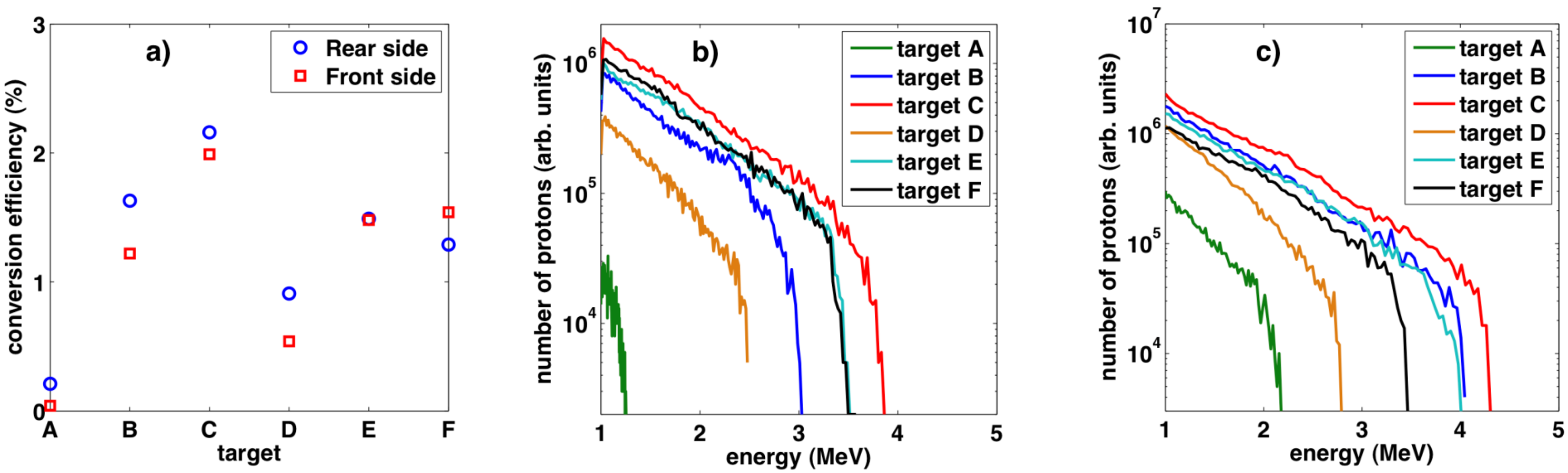
Energy distributions for flat foils have temperatures of 190 (10°) and 310 keV (45°).



Angular distributions of hot electrons isotropic with microspheres, a clear beam for the flat foil.

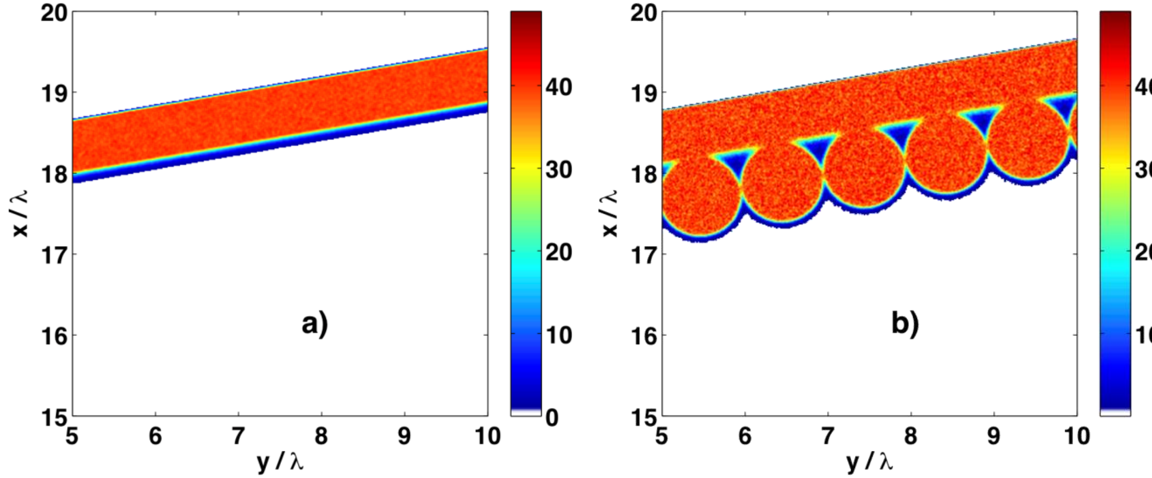
TNSA of protons

- The conversion efficiency of the laser energy into fast protons accelerated in the TNSA process from both surfaces of the thin foil (only protons with E > 1 MeV included) has similar dependence like laser absorption.
- The **highest conversion efficiency** is obtained from both target sides for the **incidence angle** of **10°** and the **sphere size** of **0.5 λ.**
- The **highest cut-off energy** is obtained from both target sides for the incidence **angle** of **10°** and the sphere size of λ.
- Laser **absorption may be boosted by presence of microscopic structures** on the laser irradiated target surface. Influence of microscopic structure on ion acceleration has not been studied previously in experiments.



Impact of finite density scale

Even very low intensity laser pre-pulse may induce evaporation from the target surface and the vapor may be ionized by the rising edge of the main laser pulse.

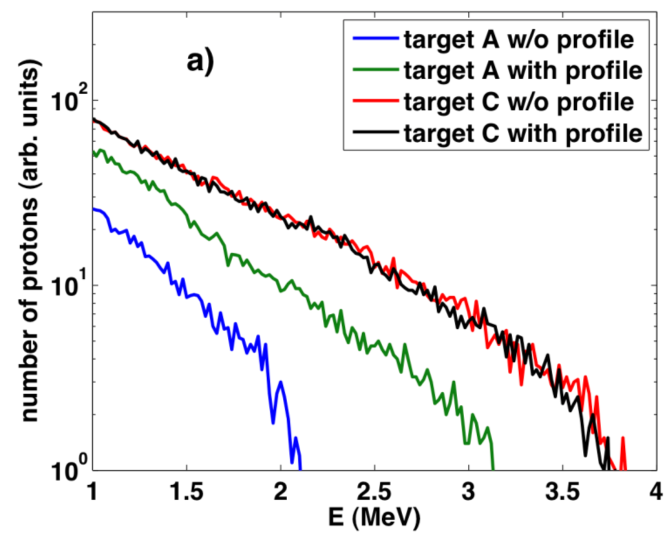


It is important to study the effect of finite (steep) plasma density profile on the target surface on ion acceleration.

The density profile is exponential for flat foil L = 0.05 λ. In target with microstructure, the profile is obtained as a result of expansion of artificially temporally heated target.

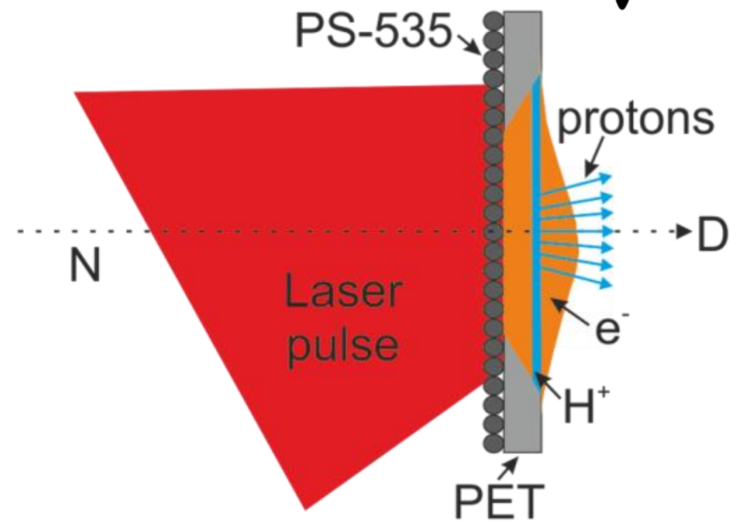
Laser absorption in flat target with plasma density gradient increases from 11 to 13%. Opposite trend is observed for the target with microspheres, decrease from 59 to 54%.

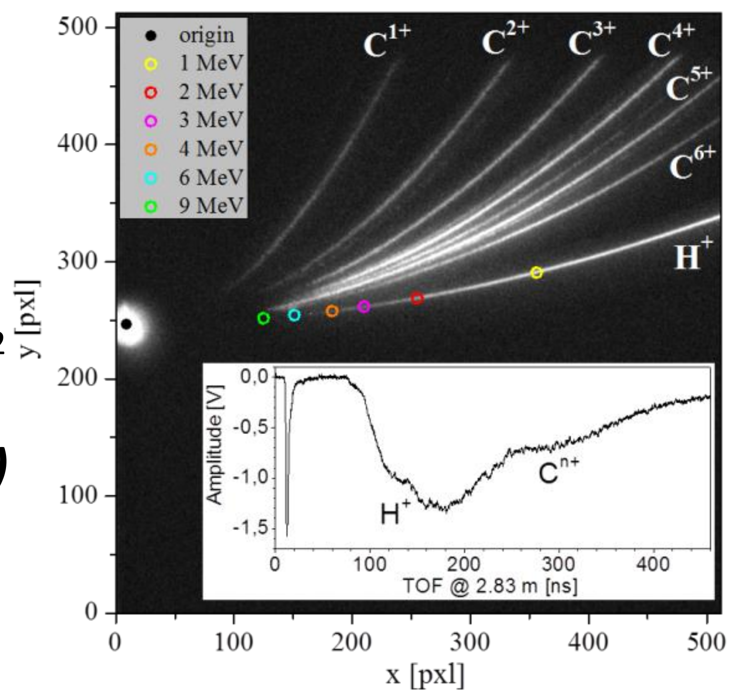
The **effect of density profile on maximum proton energy** and conversion efficiency into proton acceleration from the target rear side is **very significant** in the case of **flat foil**.



Experiment at GIST 100 TW laser

- Advanced Photon Research Institute, GIST, Gwangju, Rep. Korea, 10 Hz, 100 TW Ti:Sapphire laser
- Pulse energy 2 J, duration 30 fs, f/3 parabolic mirror, focal diameter ~5 μm FWHM
- Double plasma mirror, laser energy reduced to 1 J, maximum intensity 5×10^{19} W/cm^2, laser contrast > 5×10^{11} up to 10 ps before pulse
- Laser incidence angle was 22.5°
- Targets were pure 900 nm thick mylar foil or this foil with monolayer of polystyrene micro-spheres of diameter 266, 530 and 920 nm
- Experimental ns damage threshold 10^{11} W/cm^2

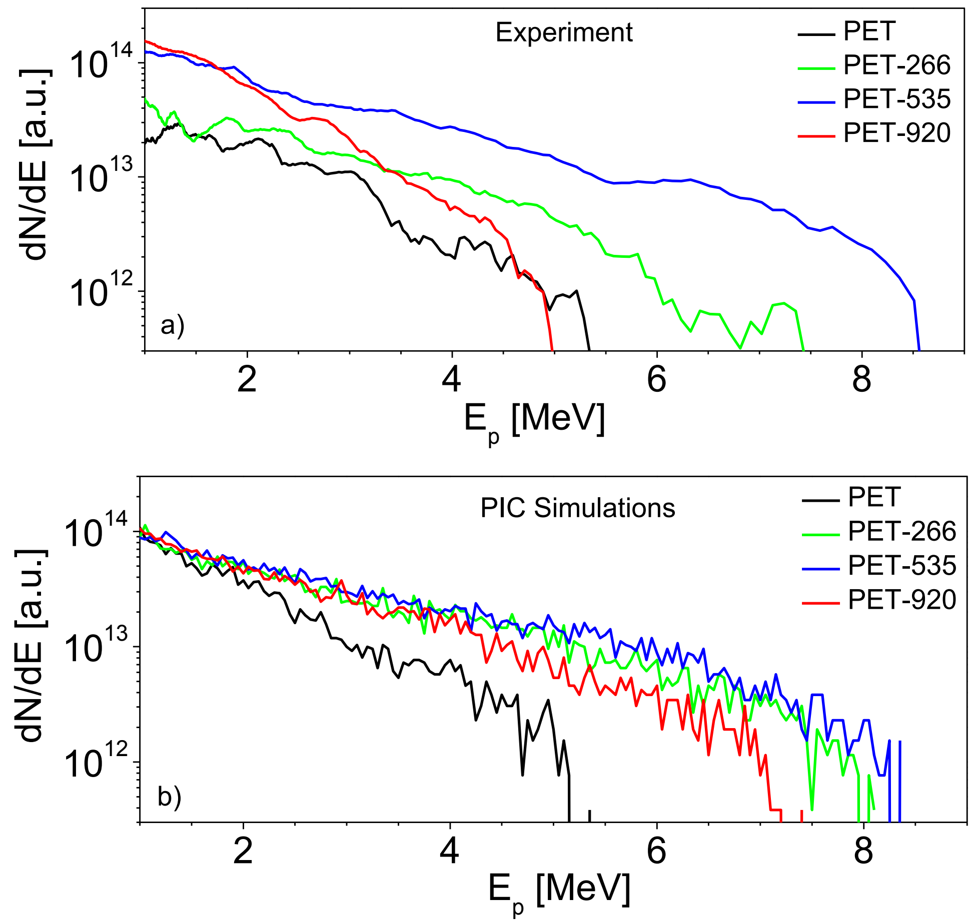




Typical Thomson parabola (0.2 T, 3.5 kV/cm) traces and signal of TOF (time of flight) detector placed 283 cm from the target

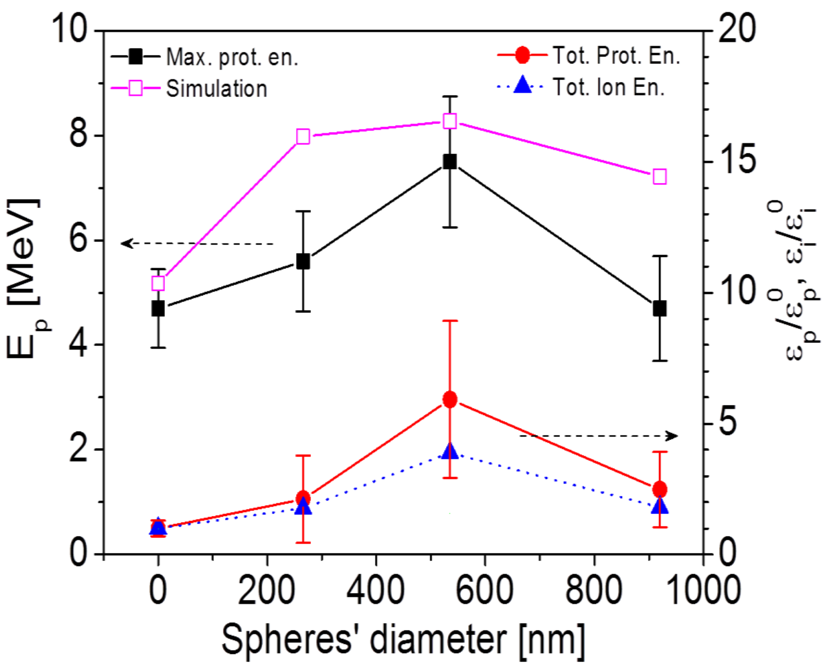
Proton energy spectra

- The proton spectra measured in the best shots in terms of maximum proton energy and number (absolute calibration is underway using CR39 data and MCP calibration, final result will present proton numbers)
- 2D3V PIC simulations carried out for the experim. intensity, incidence angle and target dimensions. Target was $C^{4+}H^{+}$, focal width was set to 2.3 μm to account for 3D difference
- The difference between pure foil and the best case of micro-spheres of diameter 530 nm is well reproduced, but …

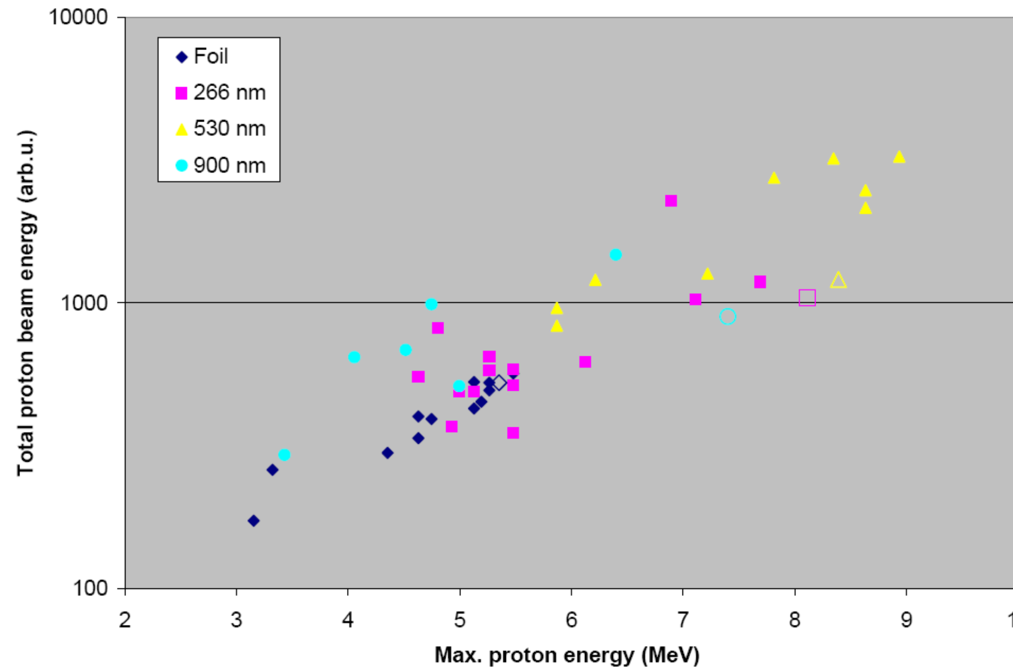


Comparison of experimental proton spectra in the best shots with spectra calculated in 2D PIC simulations

Maximum proton energy and accel. efficiency



Maximum proton energy (left axis) and laser energy transformation (right axis) to protons with energy over 0.5 MeV and to all ions (in arbitrary units) versus type target. Comparison of experiment and simulations

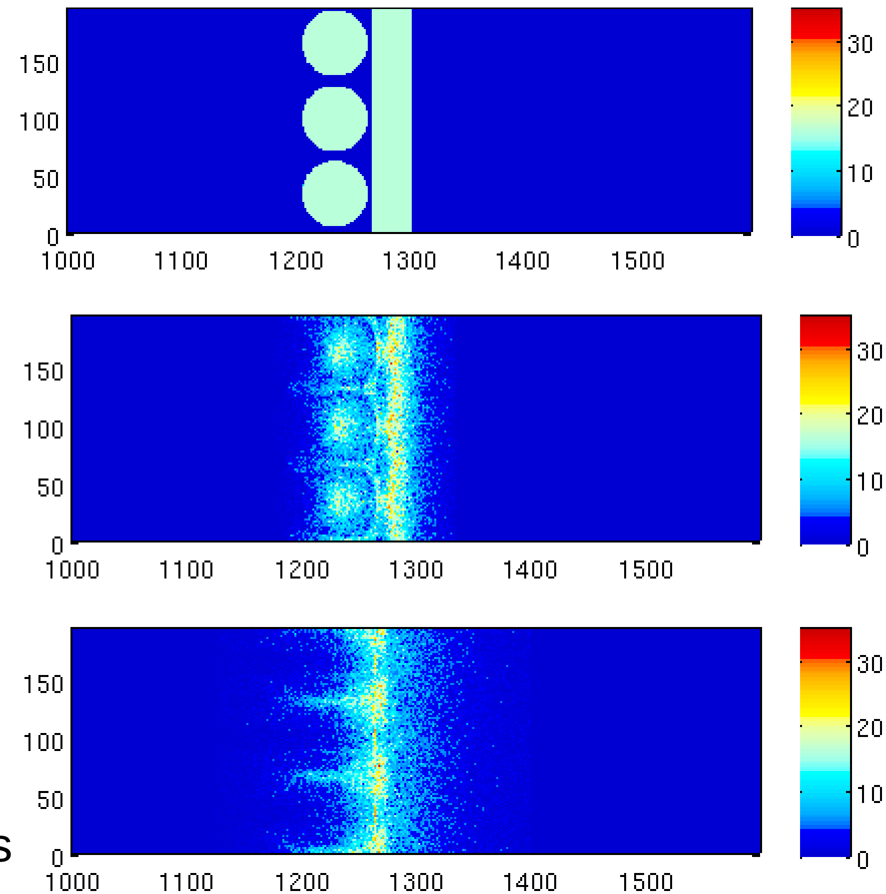


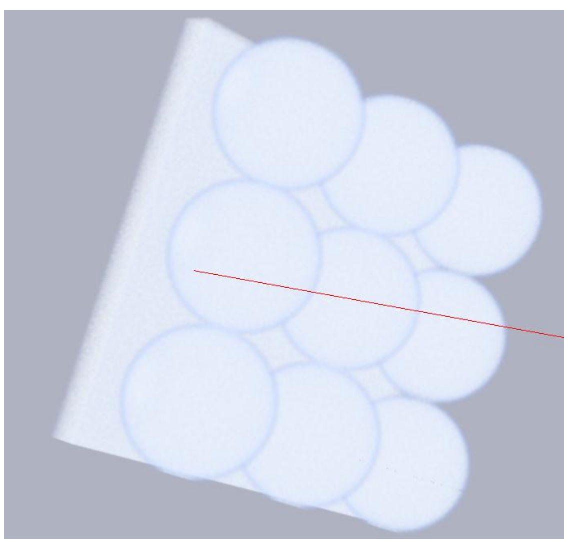
Energy conversion efficiency to protons with energy over 0.5 MeV versus maximum proton energy in experimental shots (full symbols) and in simulations (open symbols). Maximum proton enegy increased by 60% and conversion efficiency by 6 times.

3D PIC simulations

- planar wave – laser pulse absorption in 2D vs. 3D simulations – 50% vs. 49%
- lower ion cutoff energies in 3D (4.5 MeV vs. 5.5 MeV)

Ion density in various moments (section in plane, where spheres do not touch)





9 spheres, normal incidence, plane wave, periodic conditions in lateral directions

Absorption by pure 544 nm foil 19%, absorption 49% with 528nm spheres

Conclusions

- Enhancement of ion acceleration in TNSA regime by microstructure on the front surface of thin foil was proposed and analyzed
- Suitable method of target preparation was proposed and targets were fabricated
- Target damage threshold for ns prepulses was measured
- Interaction experiment on 100 TW laser facility at APRI, GIST, Gwangju, Republic of Korea **proved** proton acceleration enhancement
- Future experiments are planned at 1 PW laser at GIST
- Planned experiments at CEA, Saclay, France will also test possibility of acceleration enhancement via laser coupling to surface plasma wave.

Thank you for attention