Laser-driven proton acceleration enhancement by structured foils (simulations and experiments)

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

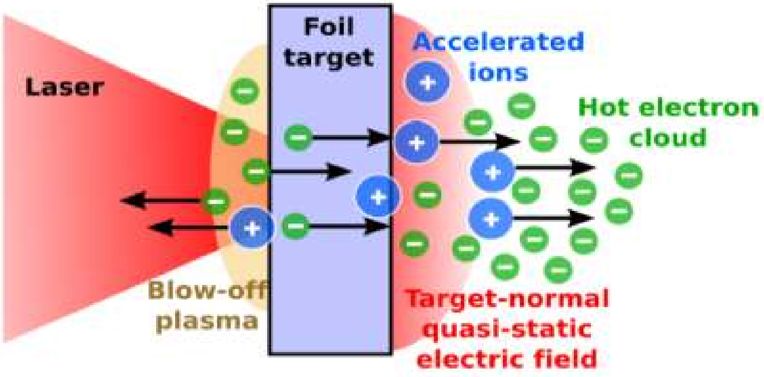
Contents

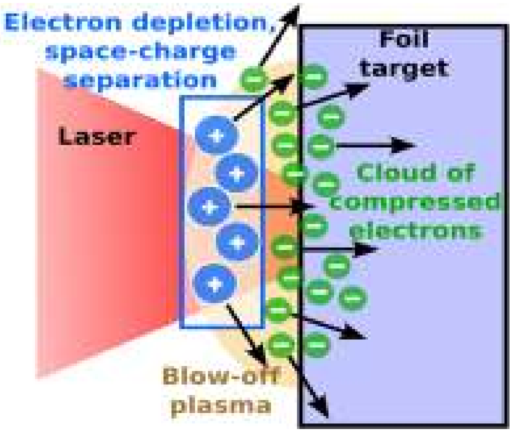
- Basic schemes of ion acceleration by laser
- Possible methods of TNSA enhancement
- Impact of microstructure on the laser irradiated foil side
- Targets with a monolayer of microspheres on thin foil
  - Optimization of the microsphere target
  - Experiment on GIST 100 TW laser
- Estimate of max. proton energy by 2D PIC simulations – reduced focal spot size
- Grid targets – foils with sinusoidal surface profile
- 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 $\sim I^{1/2}$

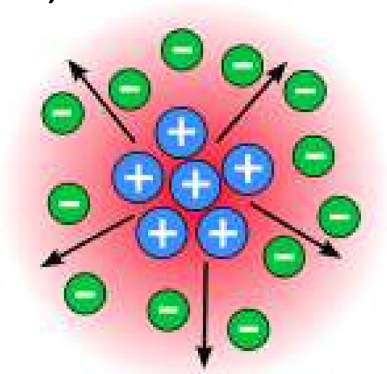
RPA difficult to demostrate at present intensities, maximum proton energy $\sim I^2$

  - **near-critical plasma** – acceleration by shock wave, soliton, …

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

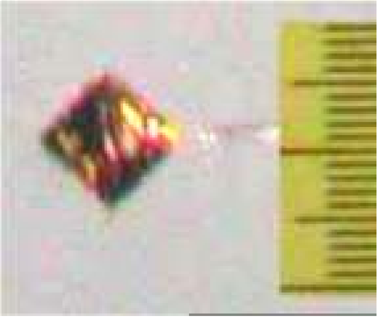
  electrons are partially but rapidly removed from the cluster, making the cluster positively charged

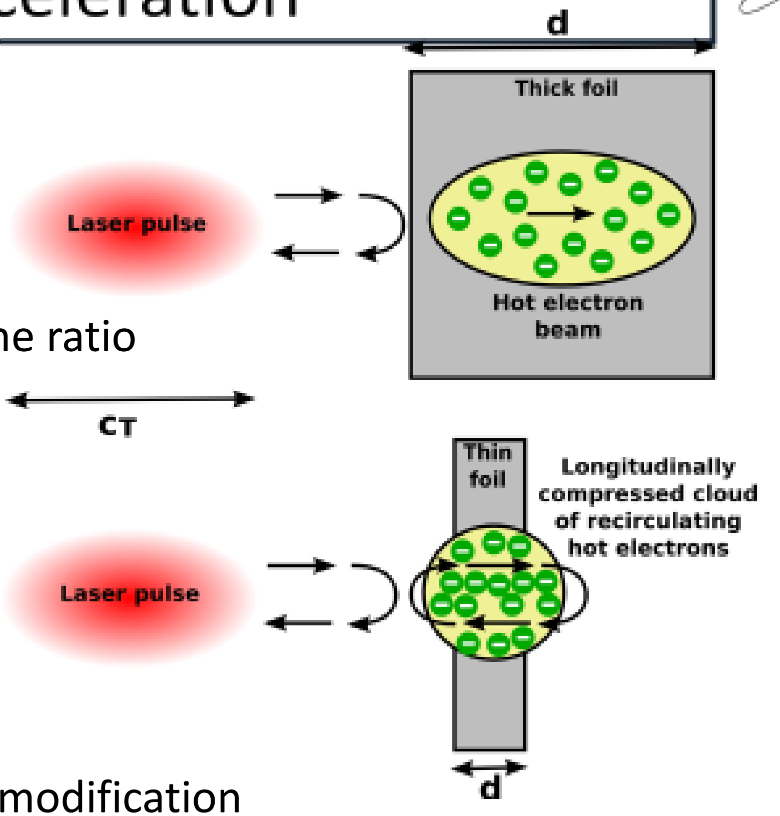
  - small clusters – **Coulomb explosion**
  - larger clusters – Coulomb explosion + ambipolar expansion



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.

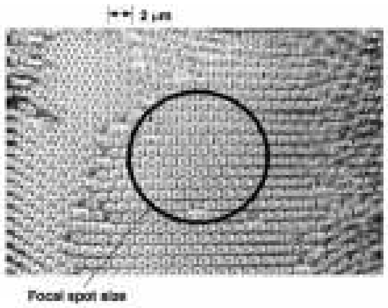


FIG. 1. Scanning electron microscope image of 1 μm diameter polystyrene spheres arrayed on a Cu substrate. The apparent dimples on the spheres are an artifact of the SEM measurement.

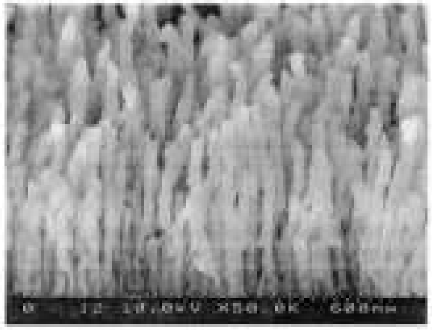
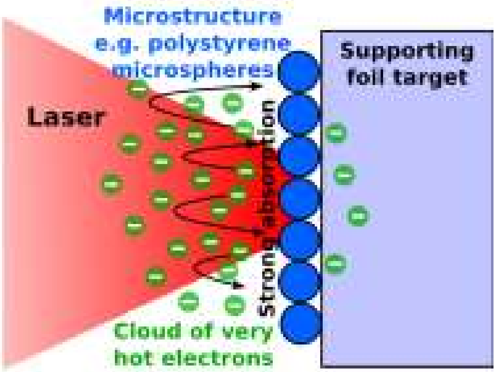


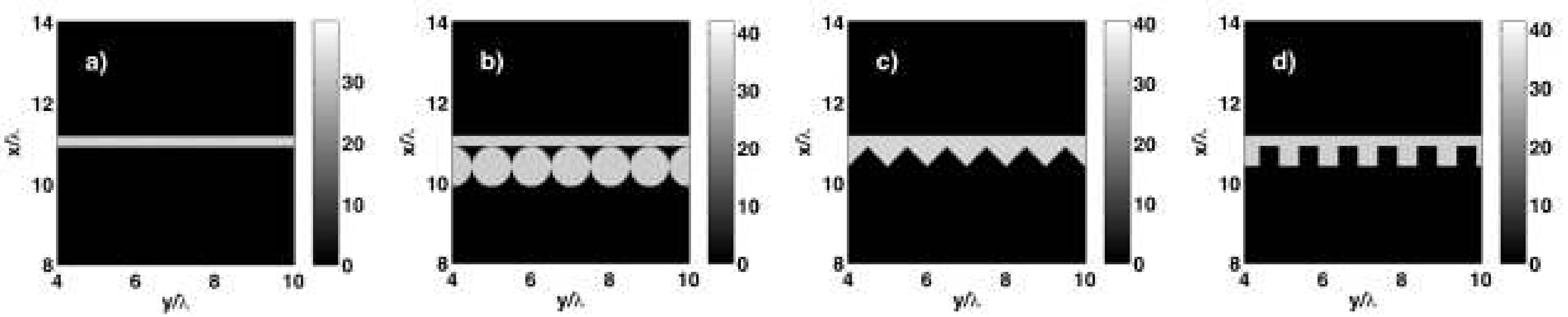
FIG. 1. Scanning electron micrograph of a Ni-nanowire target, showing a structure much like velvet fabric.



Influence of surface structure

- The influence of the shape of the surface structure studied in our 2D3V relativistic electromagnetic PIC simulations.
- 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).

Ion density



↑ 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%)

*O. Klimo et al., New J. Physics **13** (2011) 053028*

Why the absorption is higher?

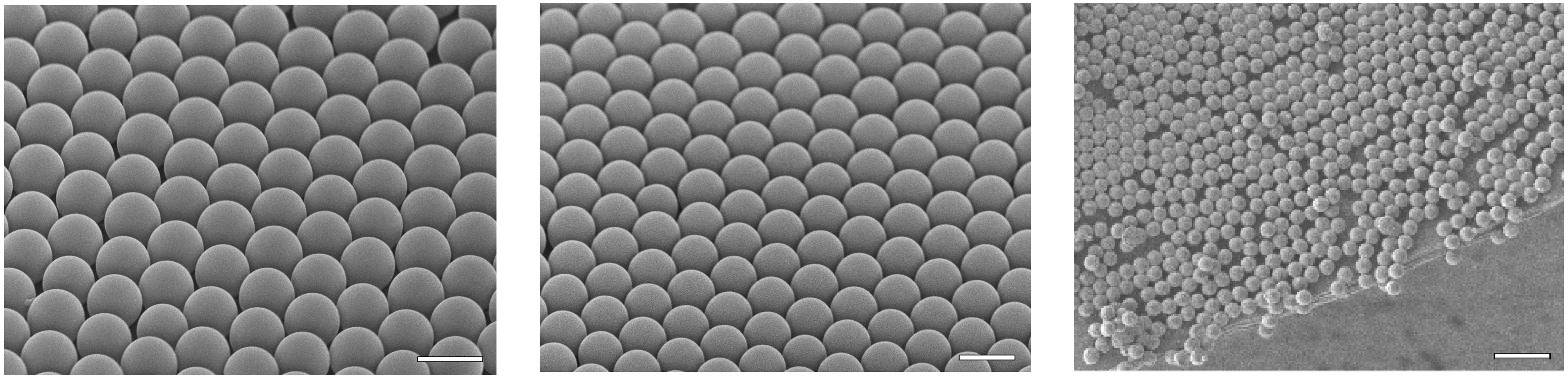
- The absorption of laser pulse energy is higher for the flat foil in the case of oblique incidence, but the difference between flat foil and foil with periodic structure is still significant.

- The nanostructure layer on the front side implies an effective larger surface area, i.e. a higher number of particles can interact with the laser field.
- The nanostructure screens the incident laser wave, but the accelerated electrons can propagate through it and, consequently be easily out of the laser wave phase, thus gaining energy more efficiently.

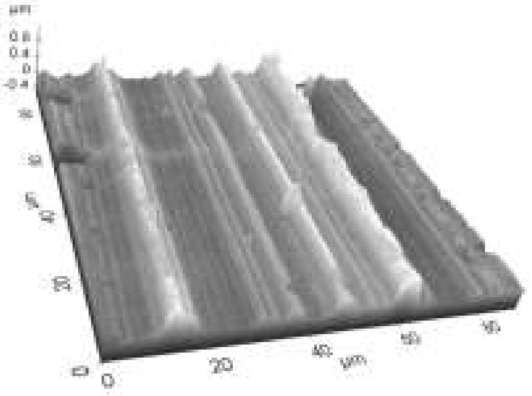
Monolayer of microspheres on foil

- 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 **simple for fabrication and optimization**.

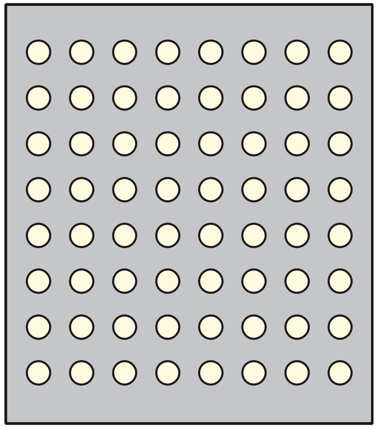
SEM images of 900 nm, 535 nm and 266 nm spheres on plastic foil



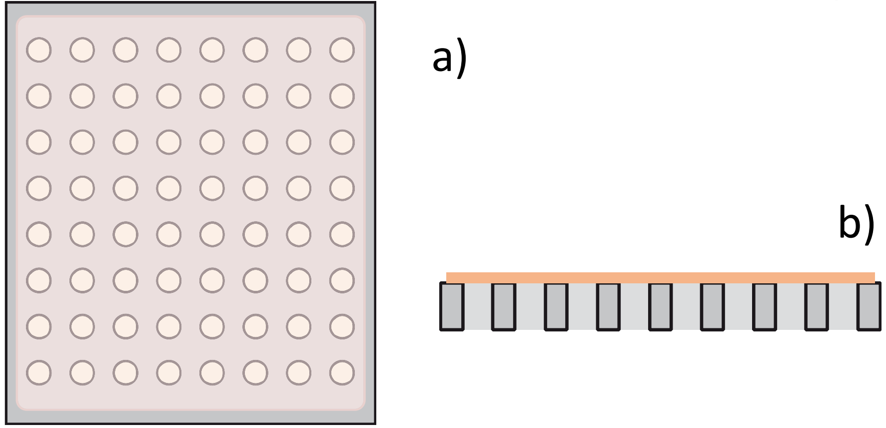
- The AFM image of commercial 2 μm thick Al foil shows irregular grating like structure with variable size of grooves probably due to the fabrication process.
- The groove size is comparable with the Ti:Sapphire wavelength and this grating can significantly influence the results of experiment (*plastic foils are smooth*)



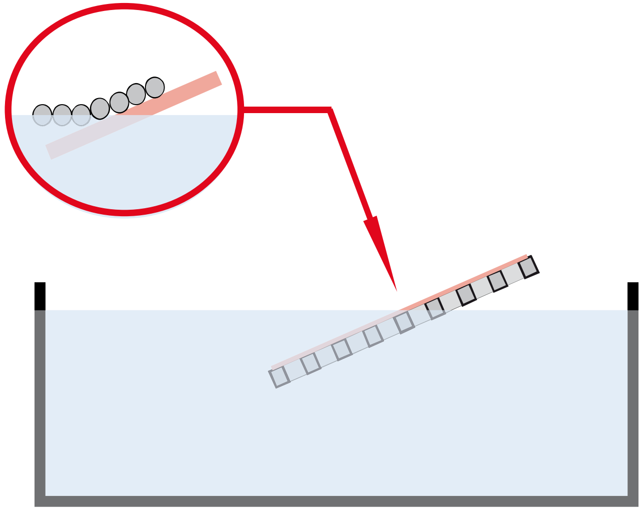
Production of microsphere targets



Aluminium holder with drilled holes



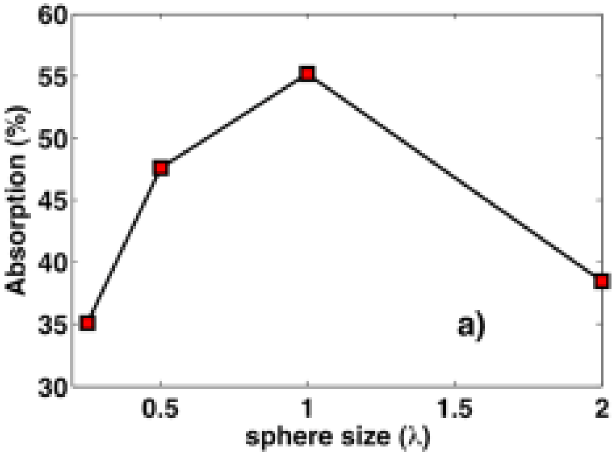
The holder overcoated with PET (Mylar) foil
a) top view; b) side view



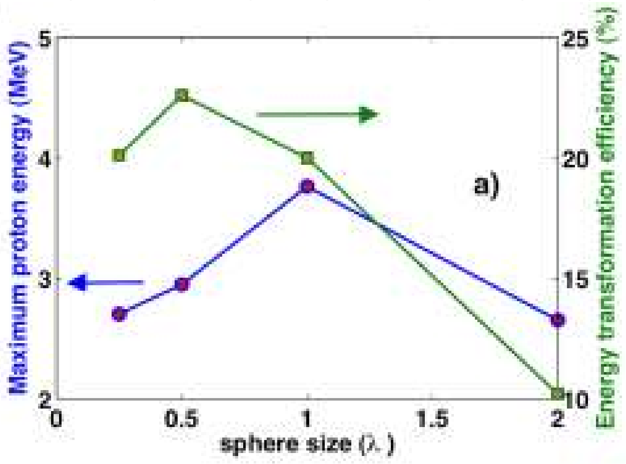
Deposition of floating monolayer on the Mylar foil

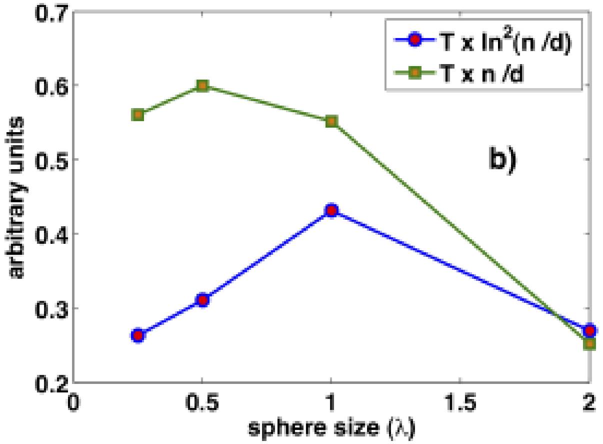
Monolayer of self-assembled PS spheres of diameter 535 nm on water surface

Optimization of microsphere size



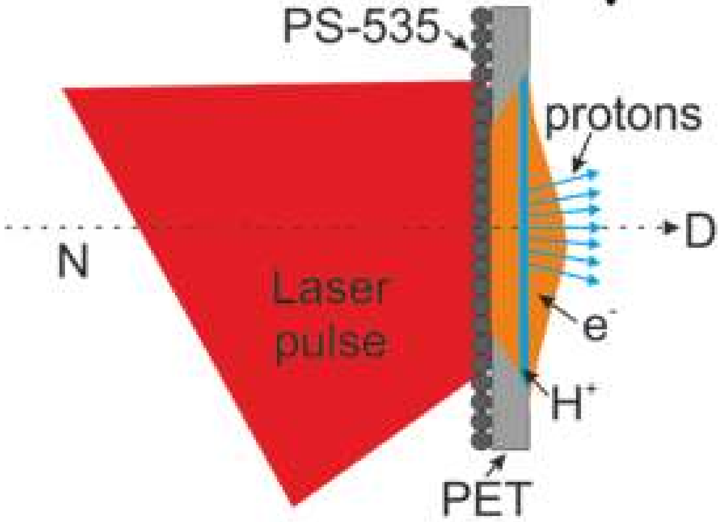
- **Optimum** microsphere **diameter** for laser absorption and maximum proton energy is **close to laser wavelength.**
- According to theory, which does not include hot electron recirculation effects, maximum proton energy scales like $E_{max} \approx T_{hot} \times ln^2(n_{hot})$, while the energy 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.

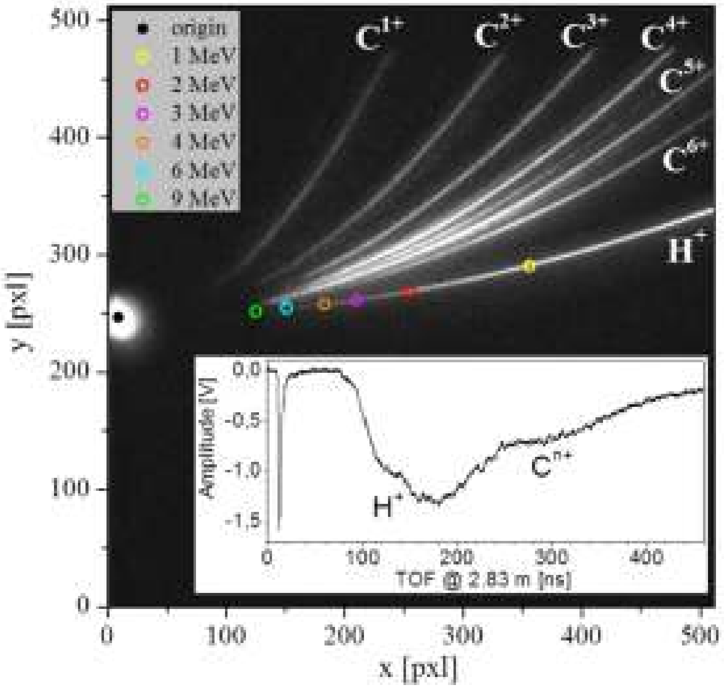




Experiment at GIST 100 TW laser

- 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 >10^9 W/cm^2

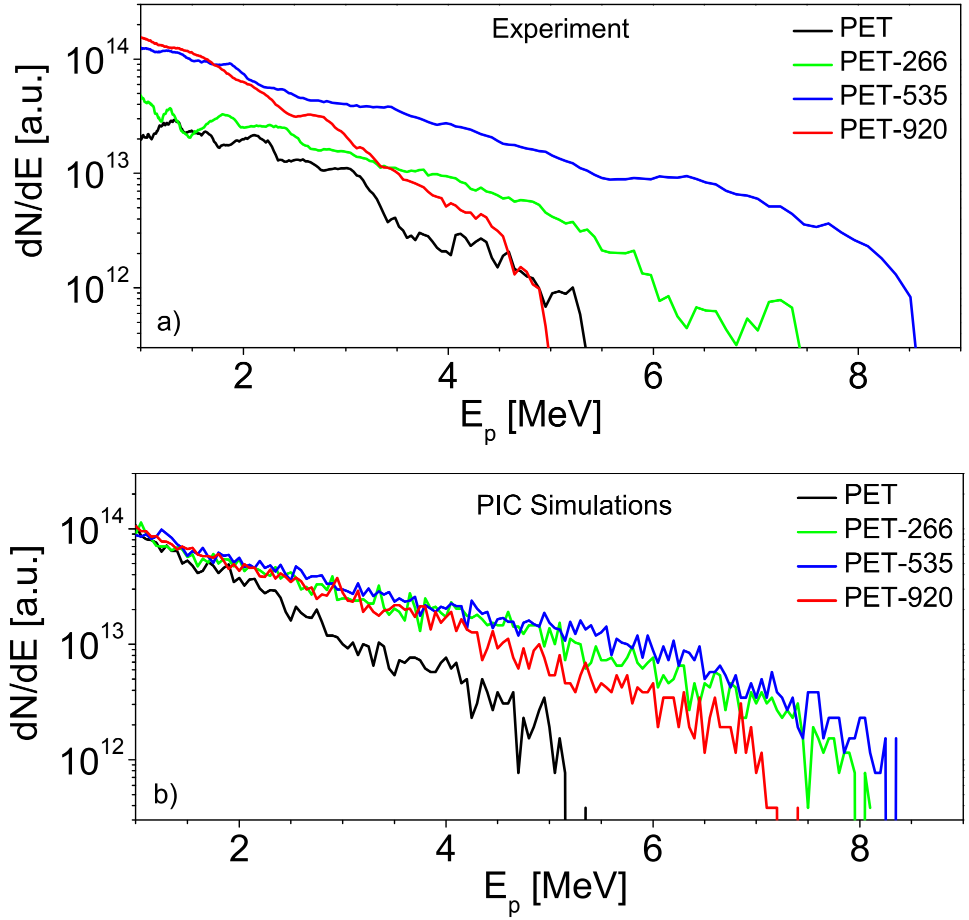




Typical Thomson parabola (0.2 T, 3.5 kV/cm) traces and signal of TOF (time of flight) detector placed 283 cm from the target

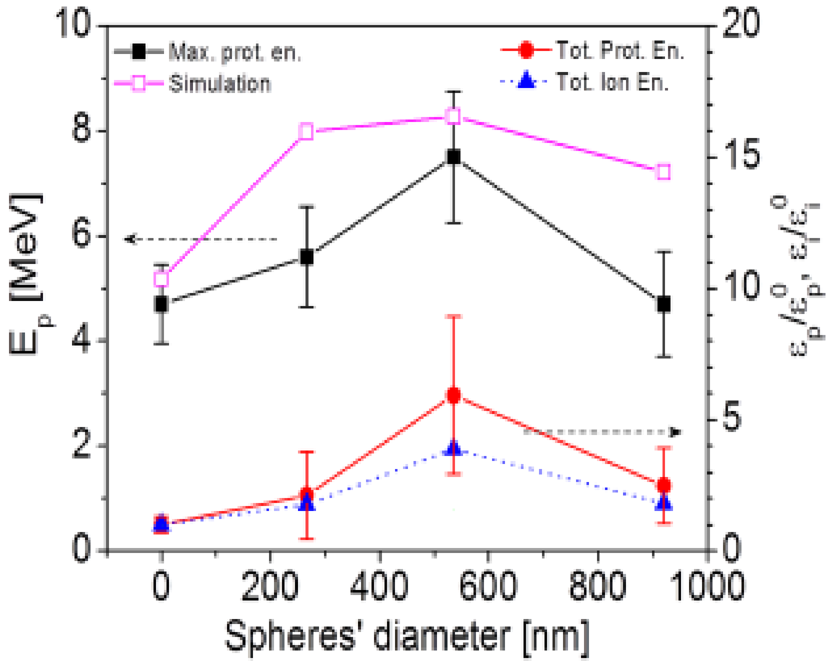
Proton energy spectra

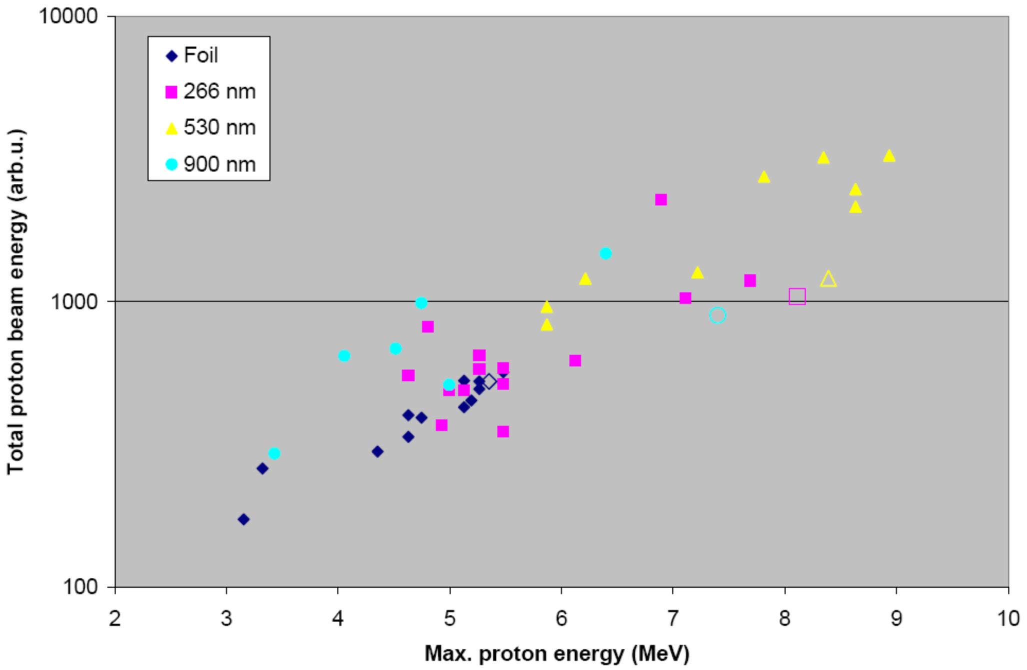
- The proton spectra measured in the best shots in terms of maximum proton energy and number (absolute calibration is underway using CR39 data and MCP calibration, final result will present proton numbers)
- 2D3V PIC simulations carried out for the experim. intensity, incidence angle and target dimensions. Target was $C^{4+}H^{+}$, focal width was set to 2 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 in2D PIC simulations

Maximum proton energy and accel. efficiency





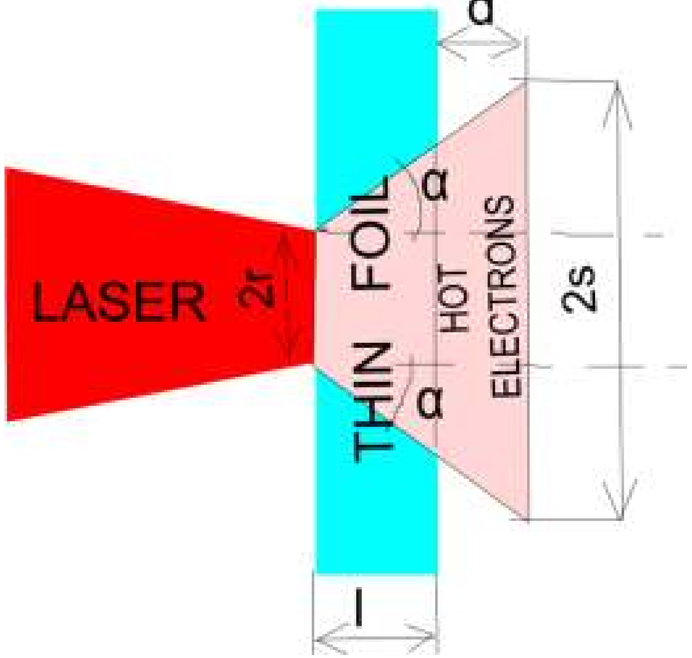
Maximum proton energy (left axis) and laser energy transformation (right axis) to protons with energy over 0.5 MeV and to all ions (in arbitrary units) versus type target. Comparison of experiment and simulations

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.

Reduced focal spot size in 2D simulations

our goal: to estimate maximum energy of accelerated protons in experiments by 2D PIC simulations (***2D simulations usually overestimate proton energies***)

problem: which focal spot size should be used in 2D simulation compared with experiment (3D case)?



r – focal spot radius
s – radius of hot electron cloud
l – foil thickness
d – characteristic distance of ion acceleration
α – hot electron beam divergence

$d = c_s \tau_L = (Z T_h/m_i) \tau_L$
$s = r + (l+d)*tg(\alpha)$

the same hot electron density at distance d is assumed for 2D and 3D case, thus $s_{2D}/r_{2D}=\pi s_{3D}^2/(\pi r_{3D}^2)$

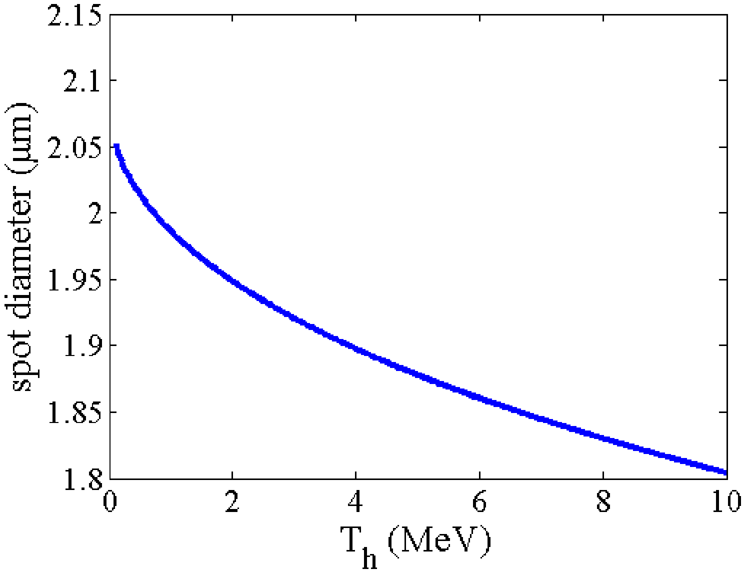
Reduced focal spot size in 2D simulations

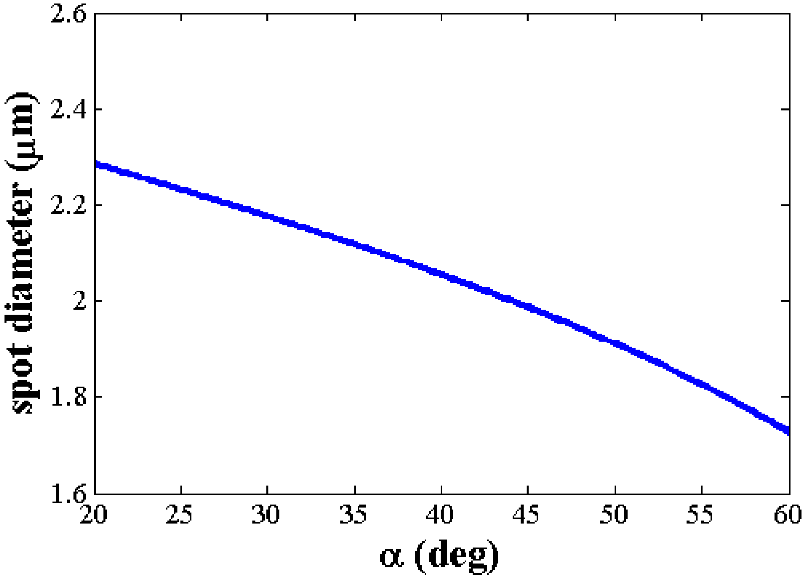
$r_{2D} = (d+l)tg(\alpha)/[((d+l)tg(\alpha)+r_{3D})^2/r_{3D}^2-1]$, where $d = c_s\,\tau_L = (Z\,T_h/m_i)\,\tau_L$

estimates of hot electron temperature T_h and divergence of hot electrons α are taken from 2D simulations, l and τ_L are experimental parameters

for experiments in Korea, we used l = 1 µm, α = 45°, T_h=1 MeV, τ_L = 30 fs,
r_{3D} = 2.5 µm … then **r_{2D} = 1.0 µm**

spot diameter (FWHM) = 2 r_{2D} does not depend strongly on estimated T_h and α

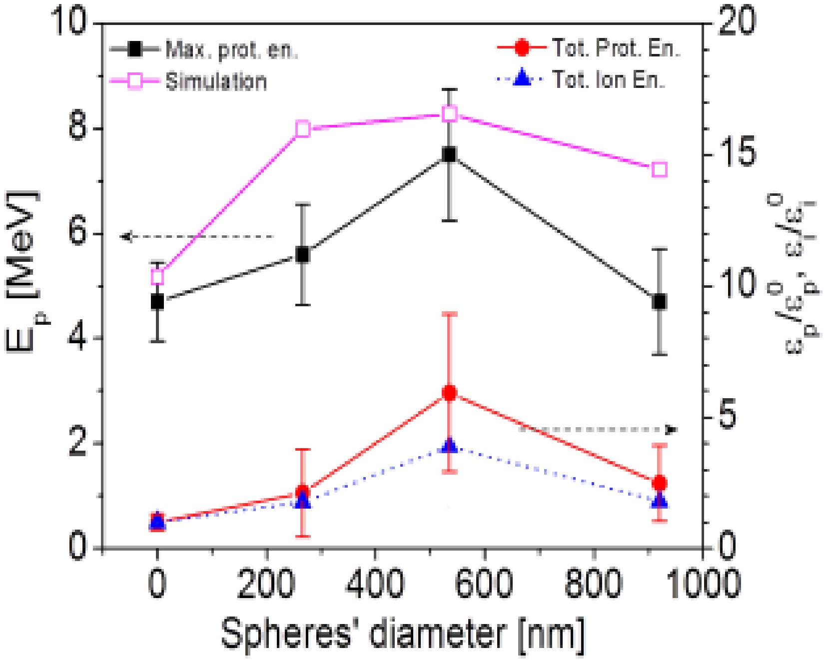




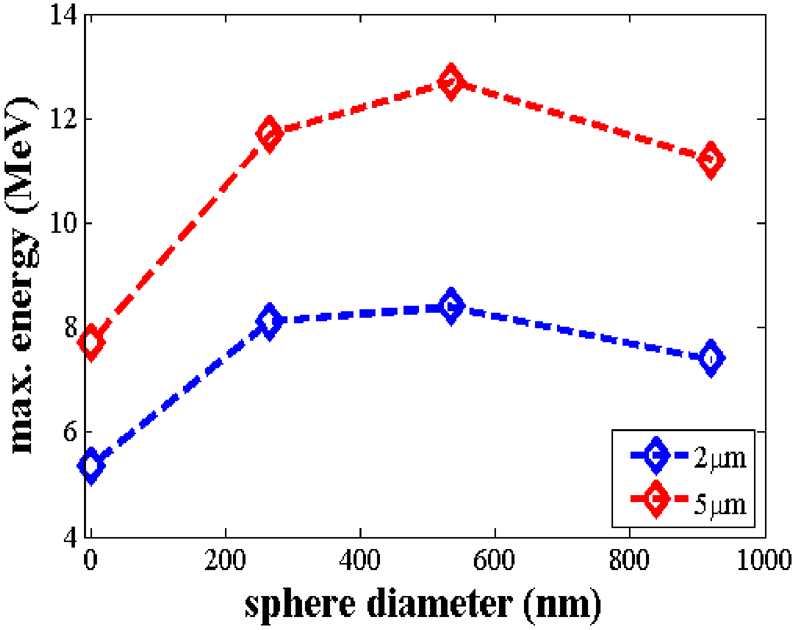
Comparison of simulations and experiment

- results of simulations with larger focal spot size does not relatively differ from simulations with reduced focal spot size, the dependence of max.proton energies (and laser-to-proton energy conversion efficiency) on sphere sizes is similar

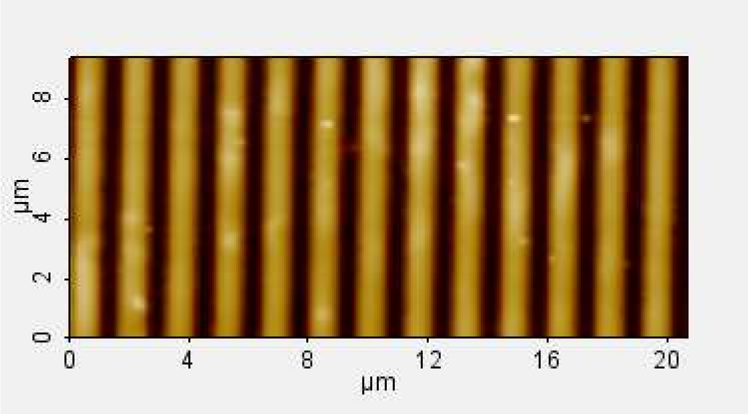
experimental results

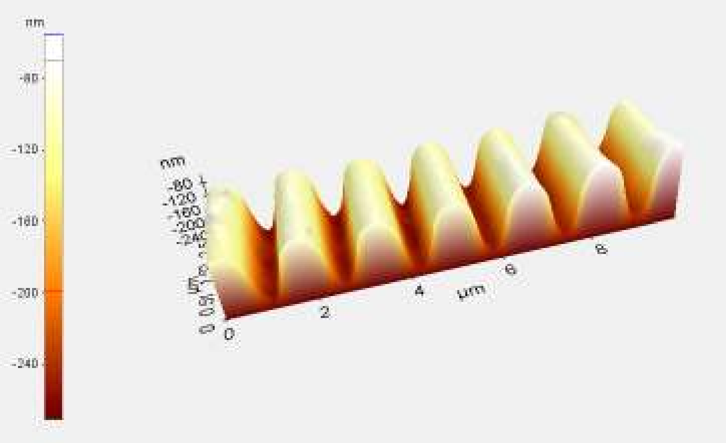


simulations with two focal spot sizes - 2 μm (reduced spot size) and 5 μm (used in experiment)

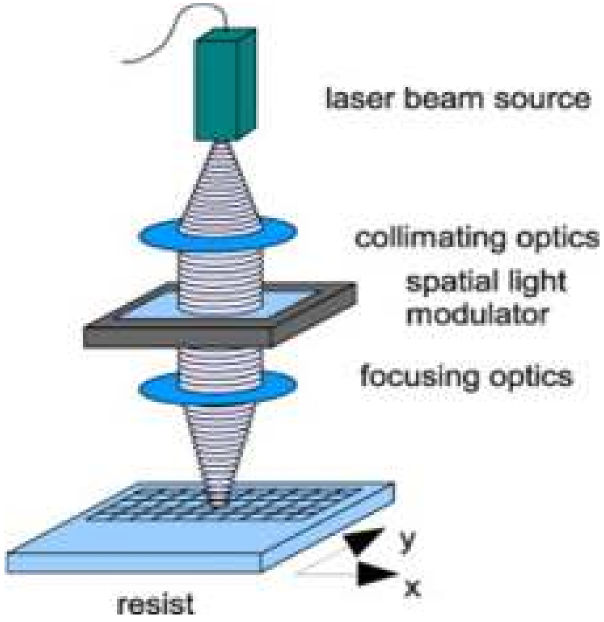


Thin grid targets - preparation

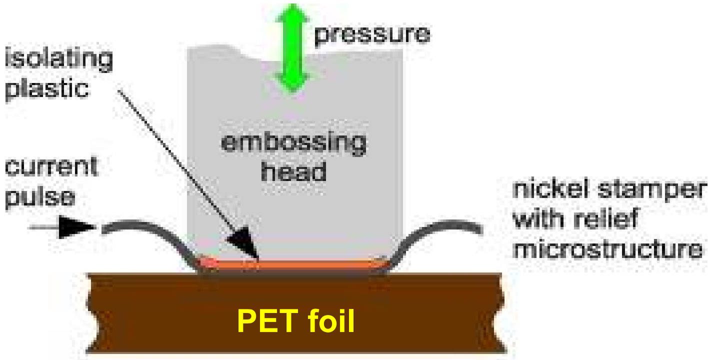




Interference lithography and thermal imprinting



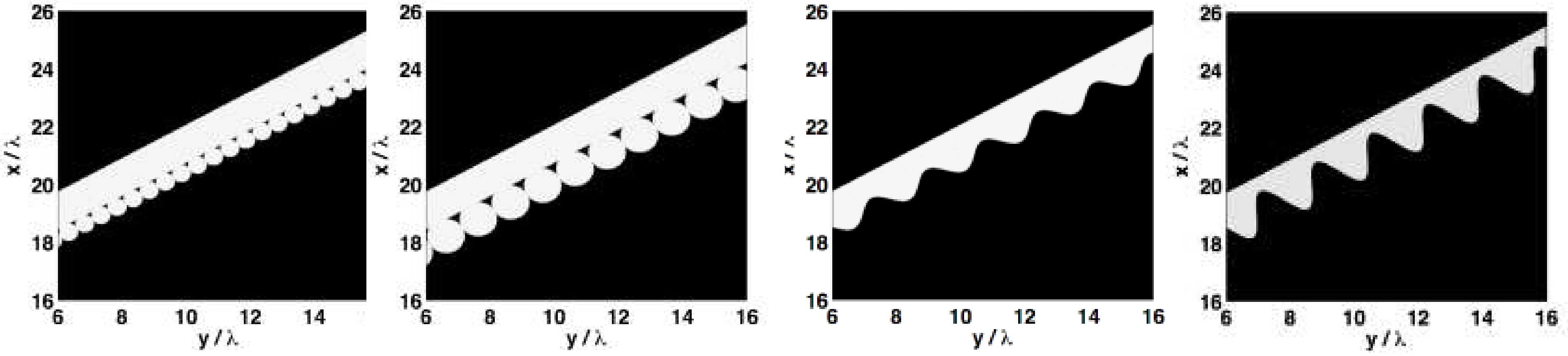
Positive photoresist spin-coated on glass Computer model of desired microstructure -> exposure



To enable mechanical embossing, the microstructures were transferred into a metal stamp using nickel electroplating

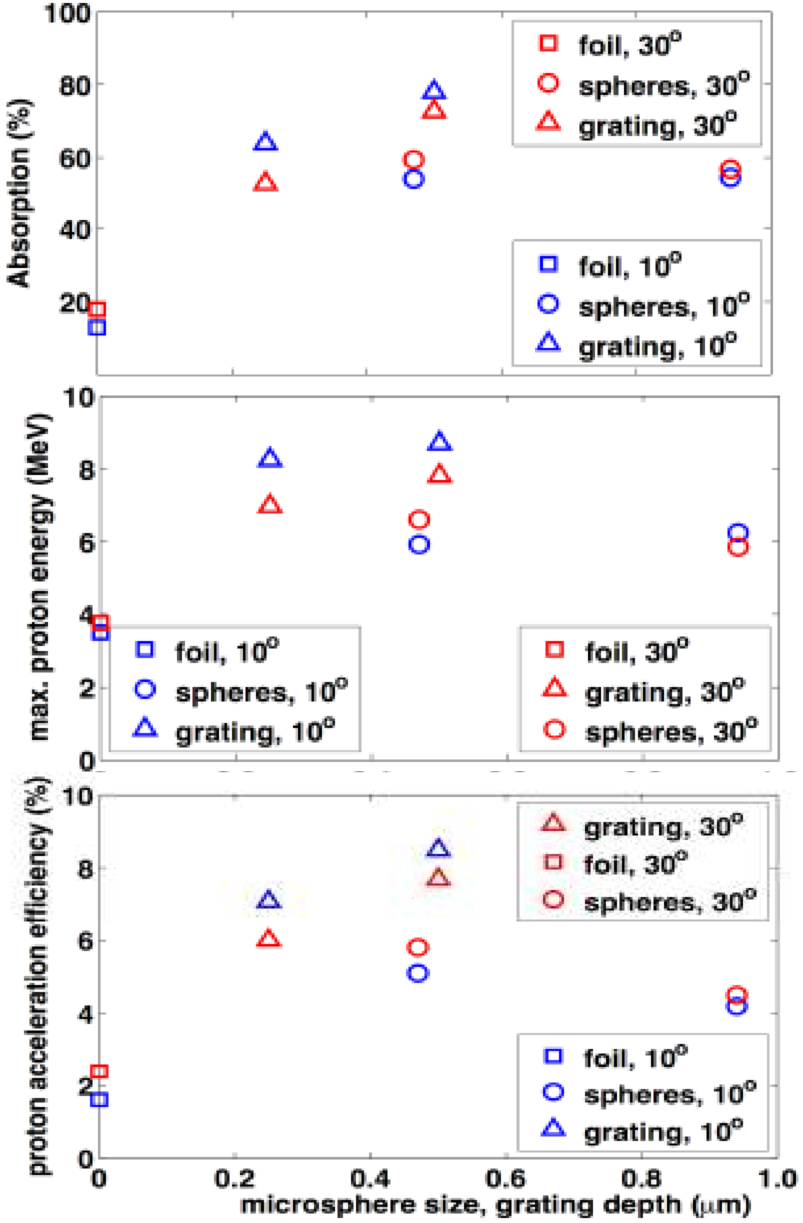
Thin grid targets - simulations

- The foil thickness 0.9 μm with and without microspheres deposited on the surface or grating embossed into the foil. The target consists of 1:1 mixture of H^+ and C^{4+} ions.
- Microsphere diameters 0.47 and 0.94 μm.
- Grating periodicity 1.6 μm and depth 0.25 and 0.5 μm.
- Resonance angle for surface plasmon wave excitation $k_{sw} = k_0(\sin\theta + \lambda / a)$, for our conditions $k_{sw} \cong k_0$ and for $a = 2\lambda$, the optimum angle is 30°. (*M. Raynaud et al., Phys. Plasmas* ***14*** *(2007), 092702*)
- Laser pulse duration 40 fs, intensity 1.7×10^{19} W/cm^2, p-polarization.
- The laser pulse incidence angle is either 10° (or 30°) with respect to the target surface normal direction.



Simulation results for grid target

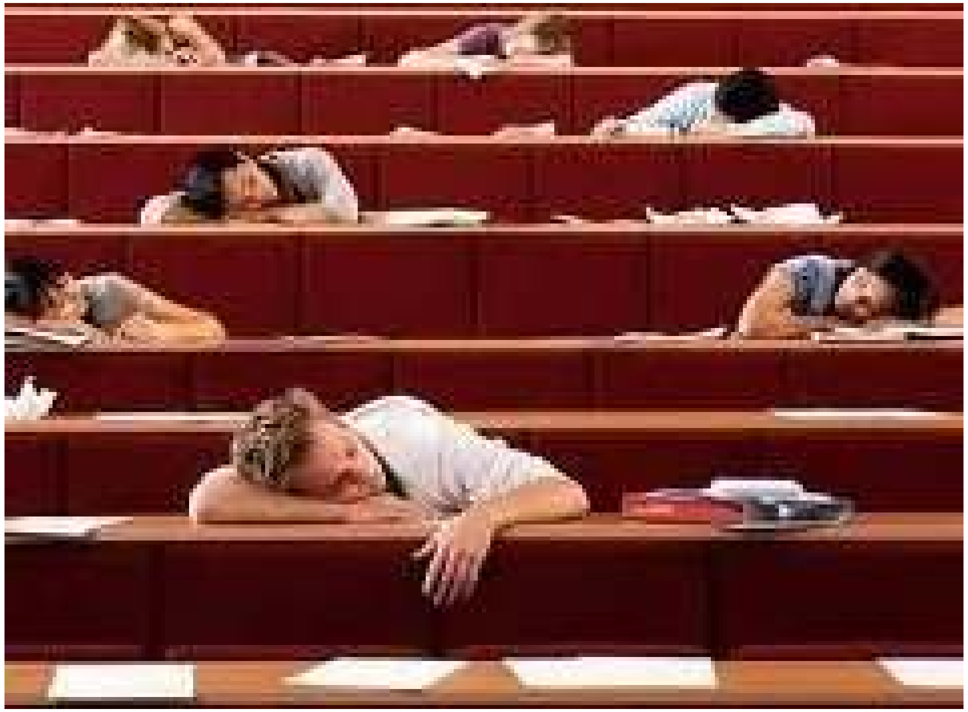
- The laser pulse **absorption** is significantly **increased** by the presence of the surface structure.
- **The grating structure is better**. Absorption increased 6 times in comparison with flat foil.
- Absorption in the grating targets increases with the grating depth.
- The maximum proton energy in gratings is increased 2.5 times in comparison with flat foil and 1.4 times in comparison with microspheres.
- The advantage of **grating** targets is not only high **absorption**, but it is possible to use **thinner** target because there is no need to support external structure.
- Another advantage is much **better stability** during transport and manipulation and possibility of **mass production**.
- Puzzle – for grating absorption for 10° > for 30°



Conclusions

- Two types of targets were developed for proton acceleration enhancement by front surface structure
  - Targets with monolayer of microspheres on foil are simple to prepare, proton energy and acceleration efficiency was demonstrated experimentally, but effective target thickness increased and individual production
  - Grid targets better for ion acceleration (simulations), mass production possible
- Max. proton energies in experiment can be estimated by using reduced focal spot size in 2D simulations
  - Periodicity of surface structure has to be smaller than the reduced spot size

Thank You for attention



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