Hollow targets for efficient acceleration of ions by ultrashort laser pulses

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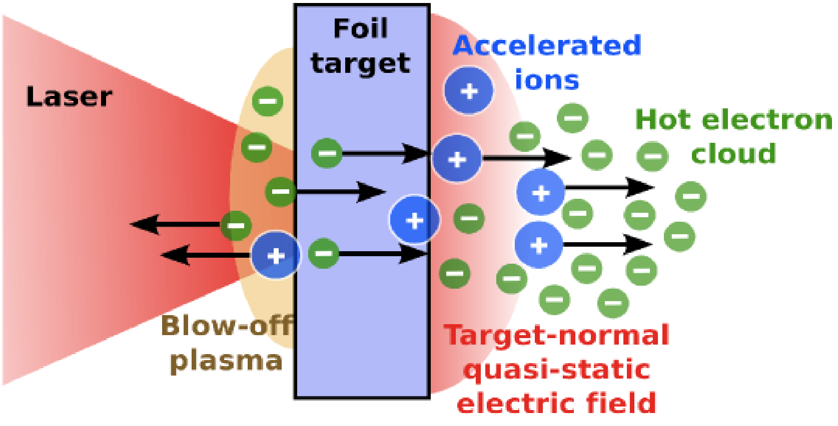
Enhancement of laser-driven ion acceleration

laser and target parameters determine ion acceleration regime and the acceleration efficiency

- target properties – thickness, density, composition, shape, surface structures, ...
- laser properties – pulse duration, intensity, pulse contrast, polarization, spot size, frequency, incidence angle ...

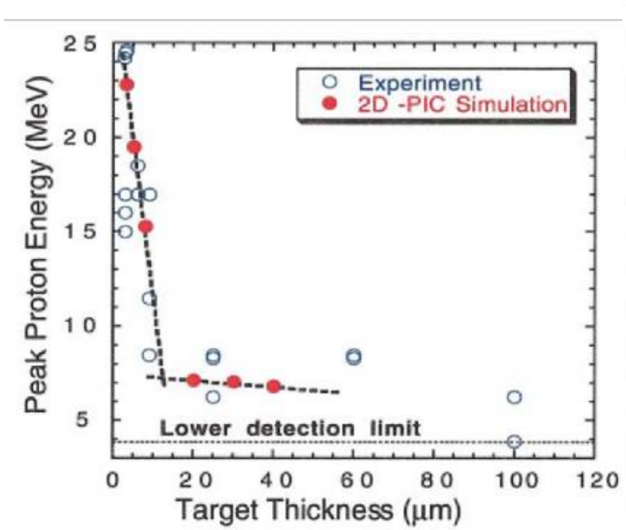
scheme of TNSA mechanism

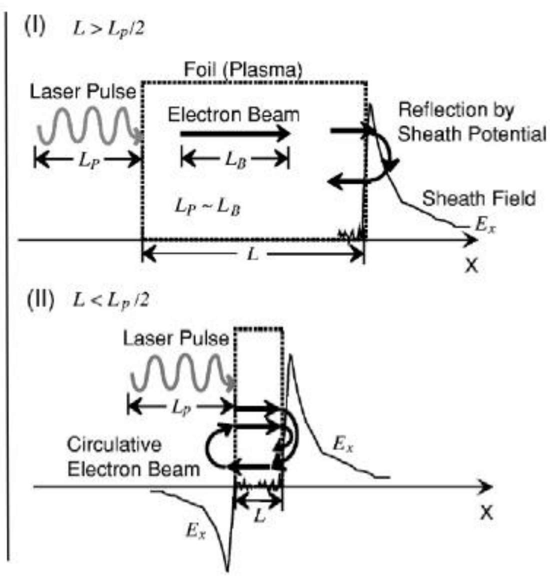


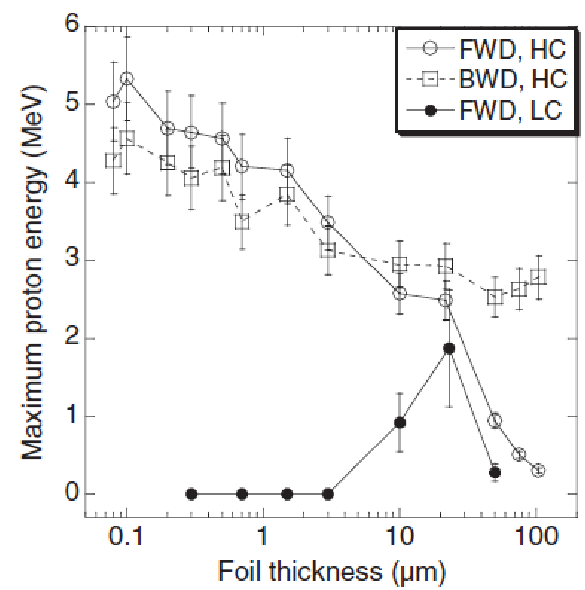
Enhancement of proton acceleration due to reduced target thickness

- explained by recirculation of hot electrons (and their angular spread) A. J. MacKinnon et al., PRL **88**, 215006 (2002)

- advanced techniques for laser pulse contrast improvements enabled to use ultrathin foils T. Ceccotti et al., PRL **99**, 185002 (2007)







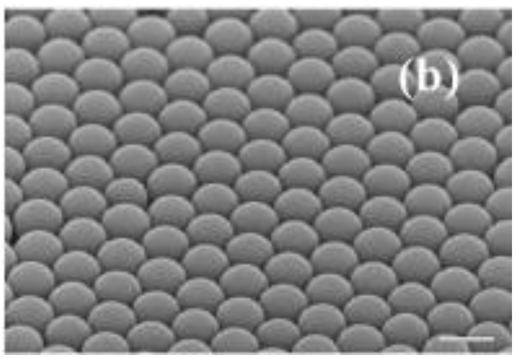
Enhancement of proton acceleration by deposited nanospheres layer

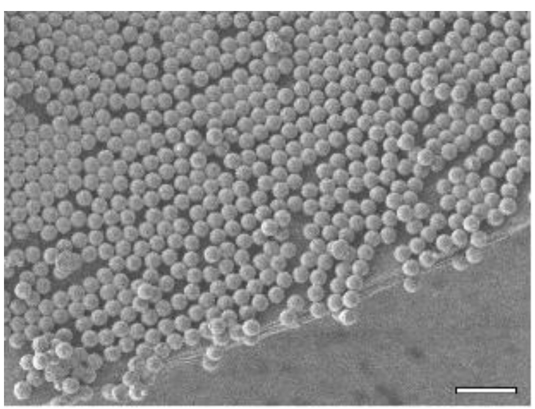
- predicted by our numerical simulations

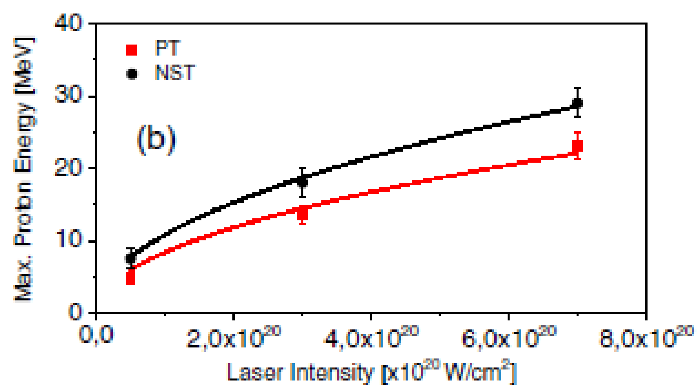
O. Klimo et al., New J. Phys. **13**, 053028 (2011)

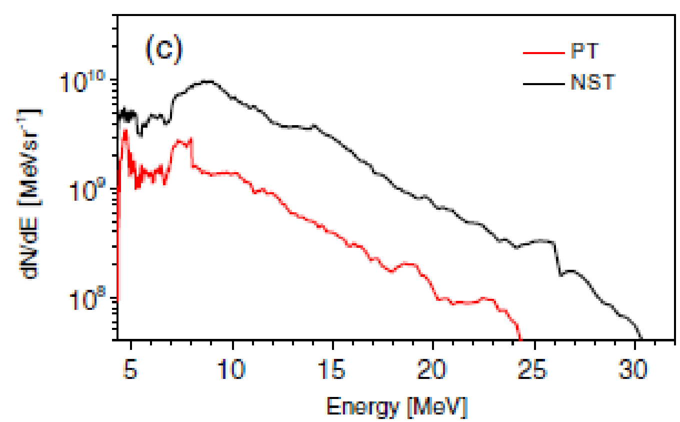
- enhancement of maximum energy and proton number observed experimentally at intensities from 5×10^{19} W/cm^2 to 7×10^{20} W/cm^2

D. Margarone et al., PRSTAB **18**, 071304 (2015)





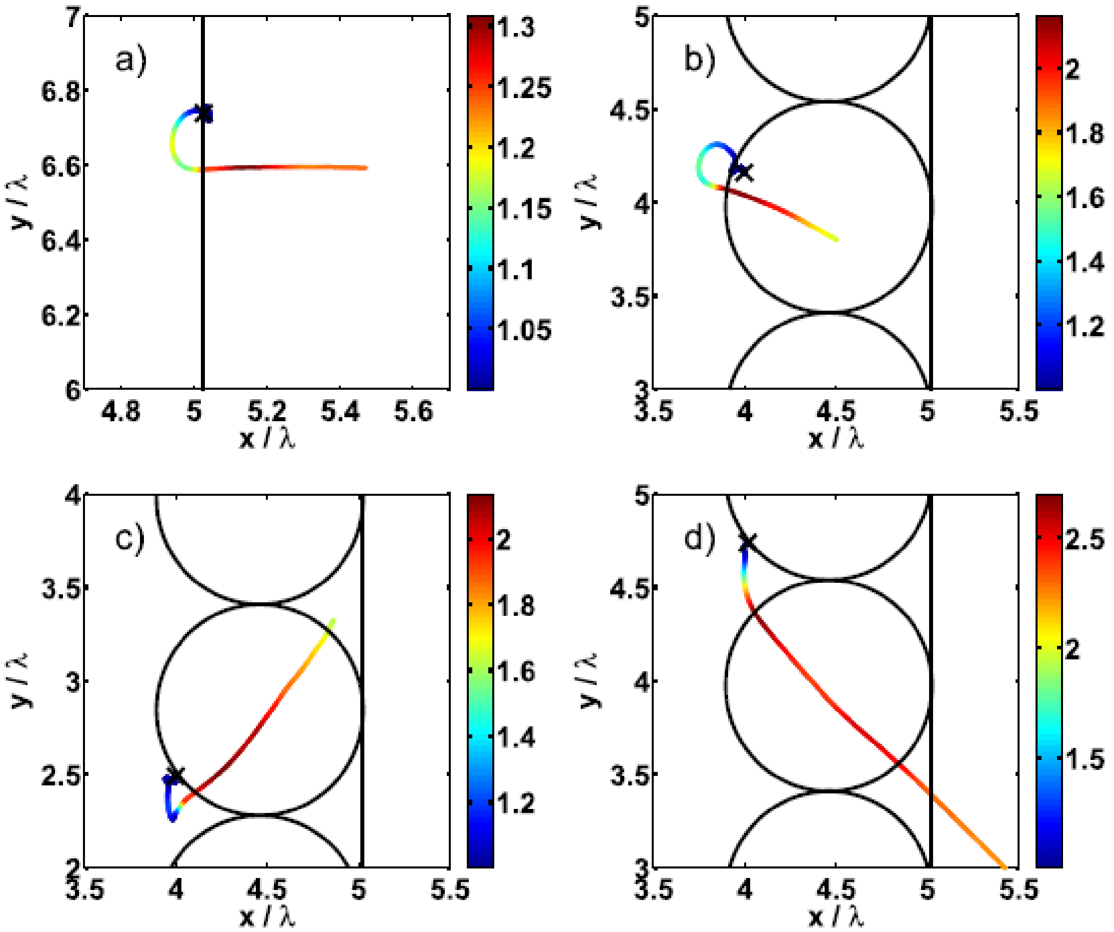




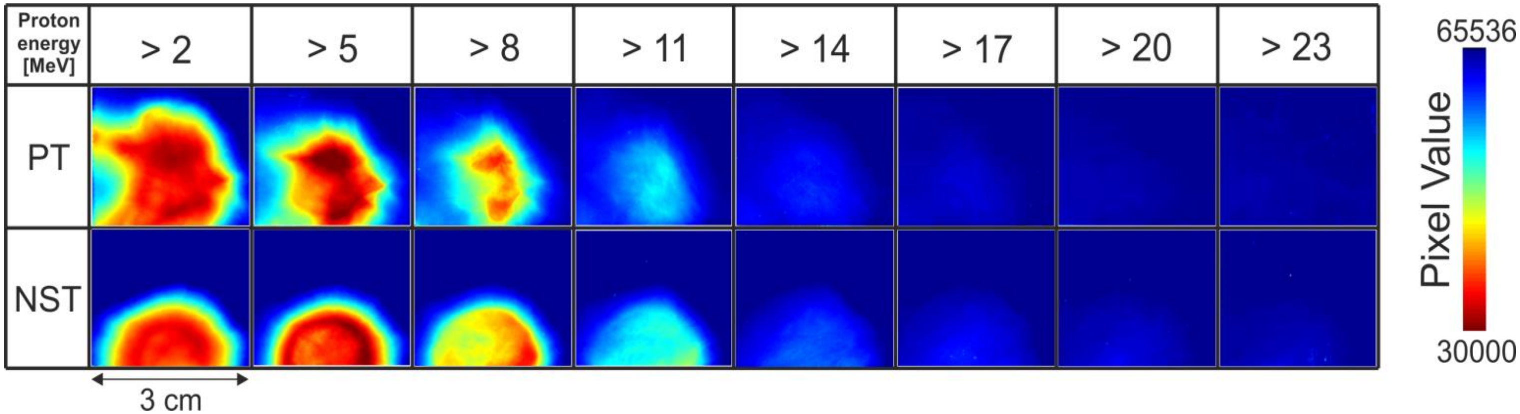
Enhanced absorption of laser energy - explanation

- hot electron trajectories

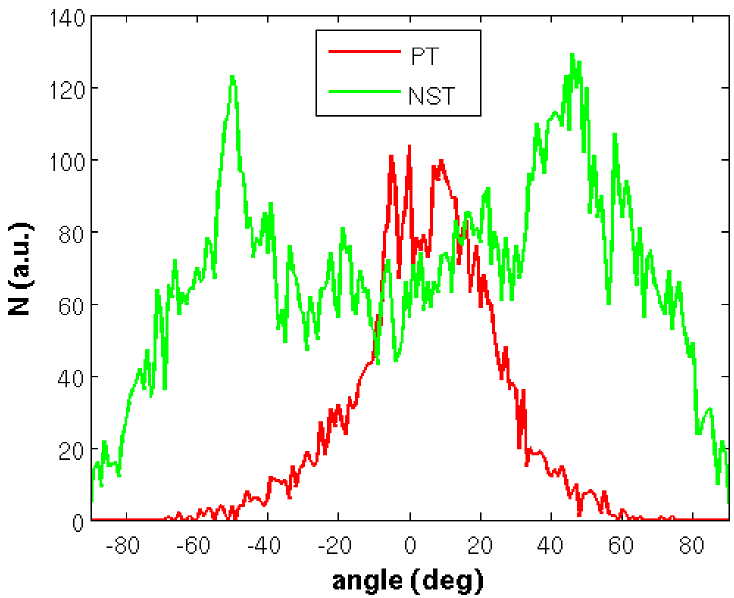
V. Floquet et al., J. Appl. Phys. **114**, 083305 (2013)



homogeneous beam profile



proton beam profile obtained from the RCF diagnostics



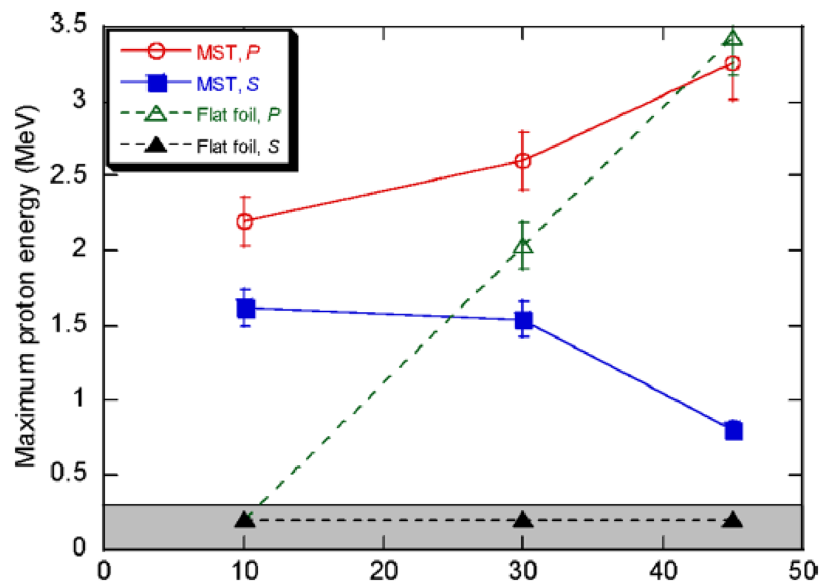
angular distribution of hot electrons;
PT = planar target, NST = nanospheres target

- a narrow angular distribution of the generated hot electrons leads to electron filamentation in the dielectric foil (inhomogeneity in the spatial profile of the accelerated protons typically appears for insulator layers thicker than 100 nm)

D. Margarone et al., PRSTAB **18**, 071304 (2015)

But… drawbacks of nano-/microspheres targets (NST/MST)

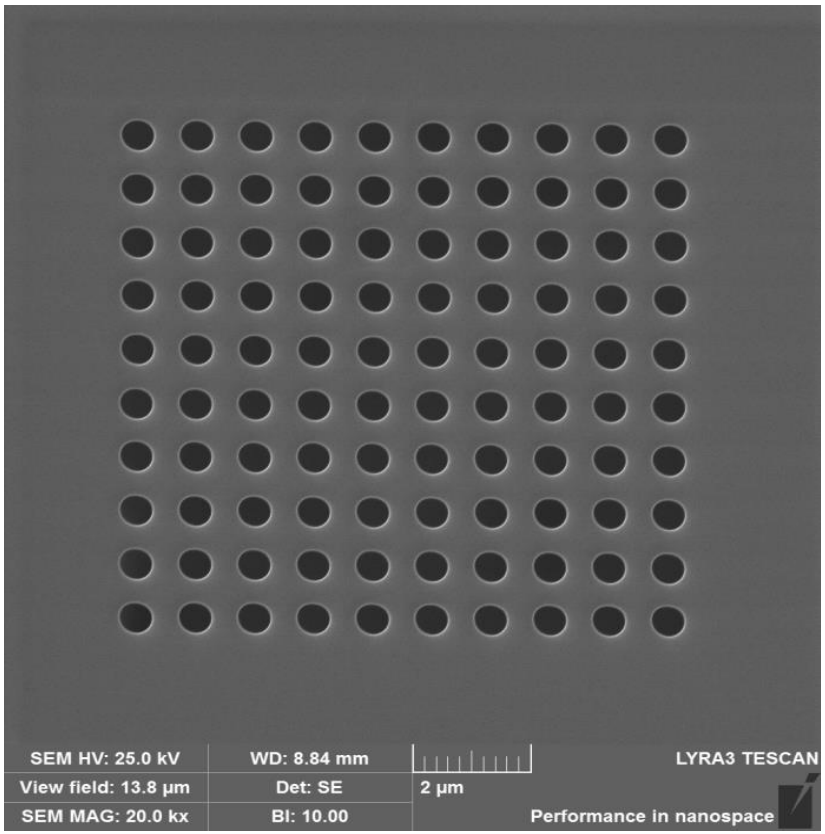
- NST proposed and successfully used due to their simple geometry and single parameter to be optimized (optimum diameter of spheres about 500 nm)
- limitations – overall target thickness (substrate + layer of nanospheres), large initial spread of hot electrons
- the efficiency of proton acceleration from flat foil is close to the efficiency for NST at larger incidence angle



V. Floquet et al., J. Appl. Phys. **114**, 083305 (2013)

Hollow targets

- developed in order to overcome the limitations in overall target thickness (substrate layer + structured layer)



the so-called "multi-hole" target was initially proposed by

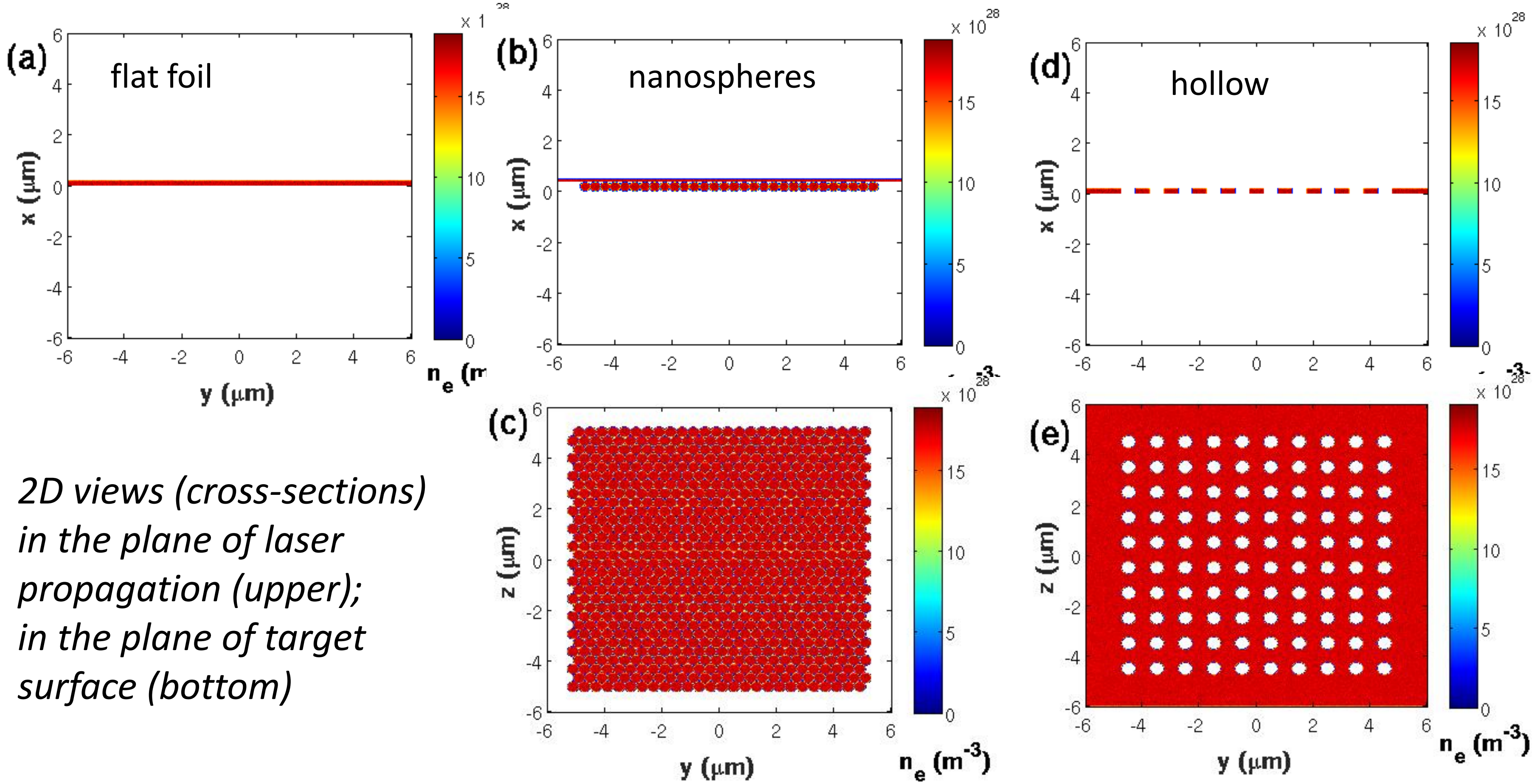
Y. Nodera, S. Kawata *et al.*, Phys. Rev. E **78**, 046401 (2008)

scanning electron microscopy image of the first prototype of hollow target (array of holes with diameter of 500 nm in a silicon nitride membrane fabricated by focused ion beam milling)

Hollow targets - 3D simulations

- optimal diameter of holes approx. 500 nm, periodicity 1 μm (preliminary 2D simulations and previous theoretical analysis)
- three types of targets investigated in 3D simulations

PIC code EPOCH used for our simulations, see T. D. Arber et al., PPCF **57**, 113001 (2015)



2D views (cross-sections) in the plane of laser propagation (upper); in the plane of target surface (bottom)

Parameters of 3D simulations

- linearly p-polarized laser pulse of peak intensity 6×10^{20} W/cm^2, wavelength 800 nm, pulse energy 3.25 J
- Gaussian temporal profile with the length of 30 fs at FWHM (in intensity), Gaussian spatial profile of the pulse with focal spot size 3 μm along y-axis and 5 μm along z-axis at FWHM (elliptical)
- the laser pulse incident on target at 10° and at 45°

- a) 200 nm thick flat foil;
  b) 200 nm thick hollow target (diameter of the holes 500 nm, periodicity 1 μm);
  c) 500 nm thick NST (diameter of nanospheres 400 nm, 100 nm thick substrate)
- $C^{6+}H_2^{+}$ plasma with initial electron density 1.75×10^{23} cm^{-3} ≈ 100 n_{ec}

PIC code EPOCH used for our simulations, see T. D. Arber et al., PPCF **57**, 113001 (2015)

one simulation takes 15000-50000 CPU core hours, 480-960 CPU cores and 0.2-1 TB RAM used (cluster Salomon, IT4I supercomputing center), ≈2-3×10^9 cells, > 10^9 particles

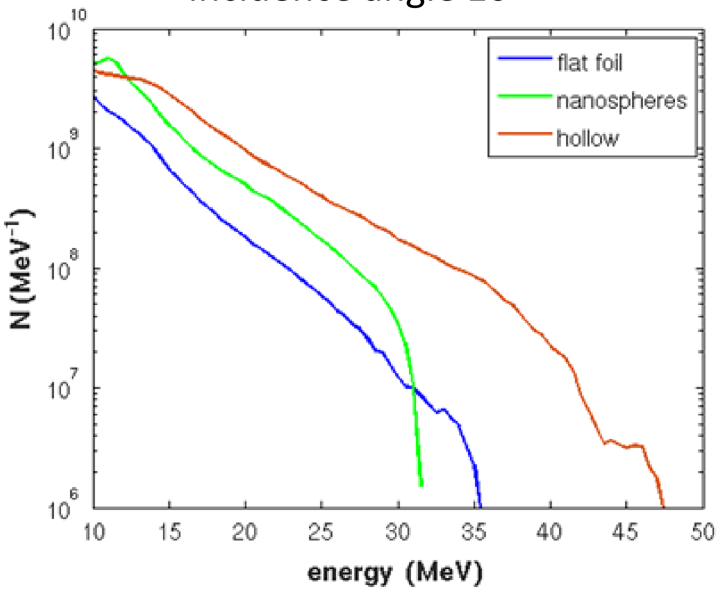
EPOCH
UNIVERSITY OF WARWICK

IT4Innovations
national@10£00
supercomputing
center100@$10!

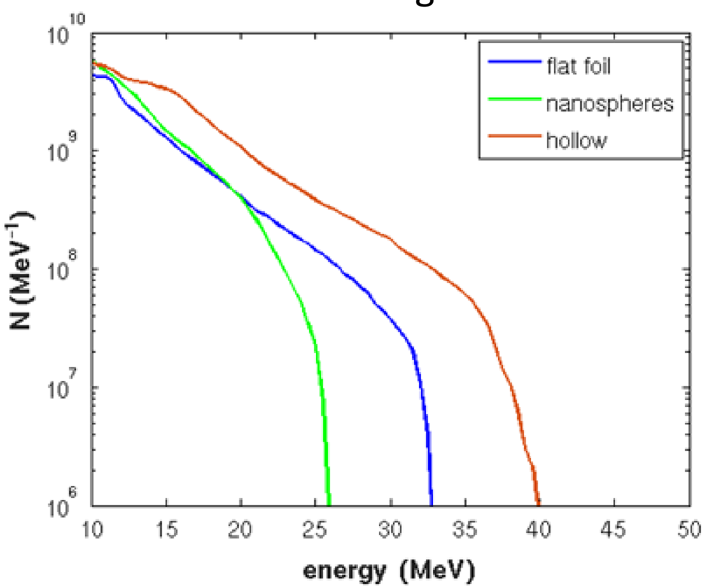
Results - comparison of the efficiency of proton acceleration

type of target	incidence angle	max. proton energy [MeV]	number of high-energy protons (E > 10 MeV)	absorption of laser pulse energy	energy transformation efficiency into fast protons	hot electron temperature [MeV]
flat foil	10	36	2.0×10^{10}	0.18	0.014	2.7
flat foil	45	33	3.2×10^{10}	0.32	0.022	3.2
hollow	10	48	5.3×10^{10}	0.42	0.043	4.3
hollow	45	40	5.8×10^{10}	0.49	0.046	5.3
nanospheres	10	32	4.0×10^{10}	0.49	0.028	3.2
nanospheres	45	28	3.4×10^{10}	0.53	0.023	3.7

incidence angle 10°

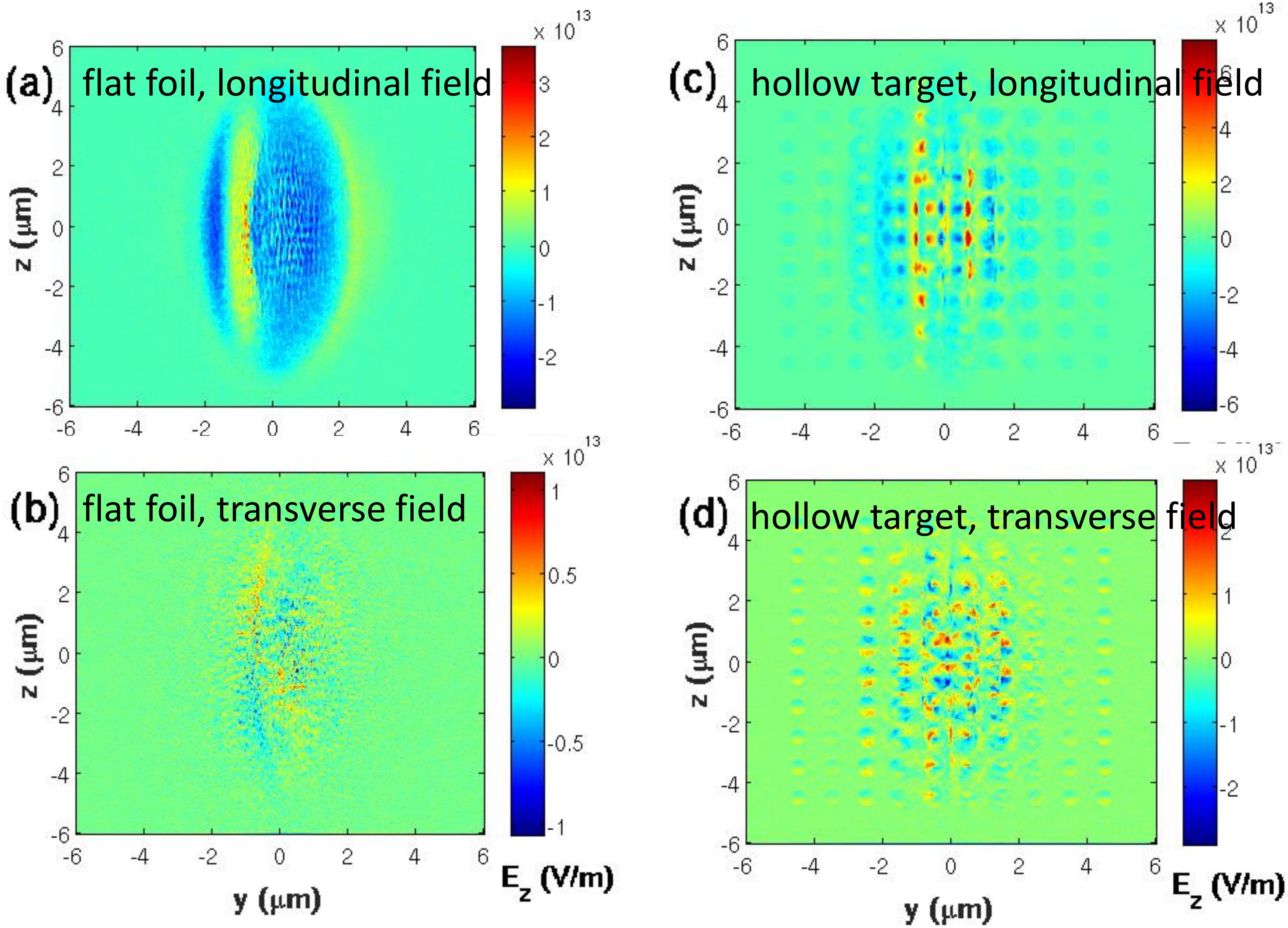


incidence angle 45°

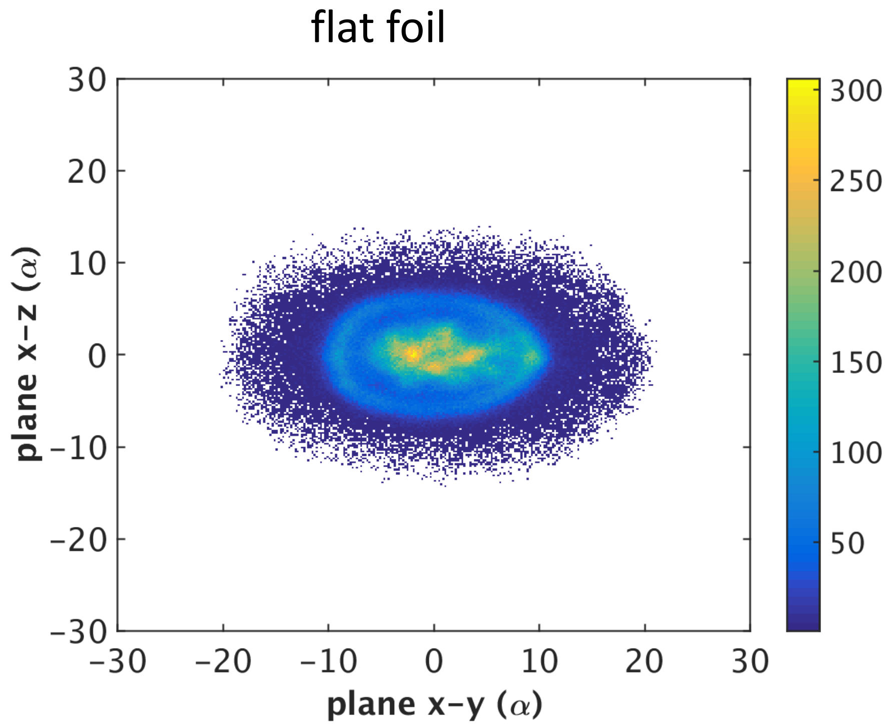


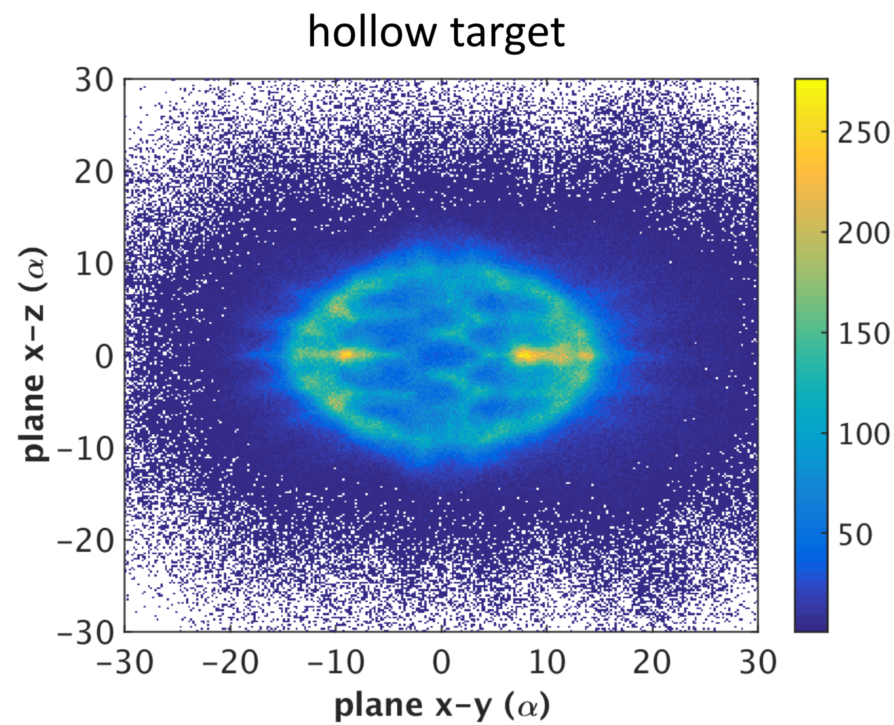
Electric fields in the target surface layer

- local enhancement of the electric field in the presence of holes compared with planar target => larger heating of electrons



Angular distribution of accelerated protons (E > 10 MeV)

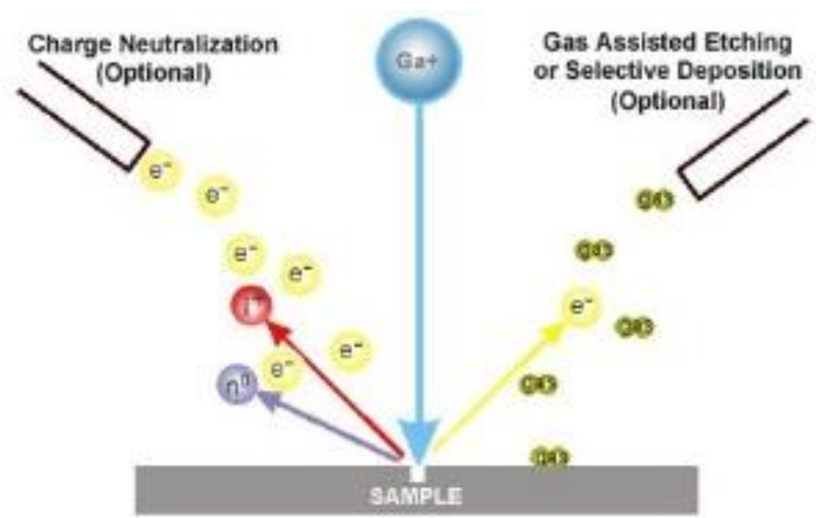


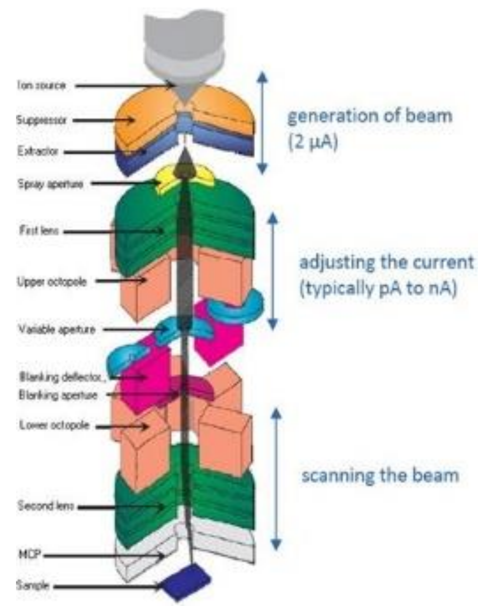


- broader angular distribution of protons in the case of hollow target
- angular spread could be reduced by making the holes only on the front surface, not through the membrane

Focused ion beam (FIB) milling

- liquid metal ion source – gallium
- Ga^+ ions accelerated to the energy of 30 keV, medium ion beam current of about 200 pA (to avoid surface roughening and to keep short fabrication times)
- SiN thin films used (available in thicknesses down to several tens of nanometers with lateral dimensions up to centimeters)
- Pt coating (layer of a few nm) –conducting surface to avoid charging of the SiN film – can be chemically removed after milling process





Conclusions

- it has been already proved in several experiments that surface structures can enhance proton energy and number of accelerated protons
- higher quality of proton beam profile using nanospheres targets
- optimum characteristic size of surface structure about 500 nm
- hollow targets are promising alternative to the structures deposited on the substrate, their advantage is mainly in decreasing of target thickness, generation of hot electrons with higher temperature, and smaller initial spread of hot electrons compared with nanosphere target

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