Enhanced proton acceleration from ultra-thin foils with non-periodic nano-holes

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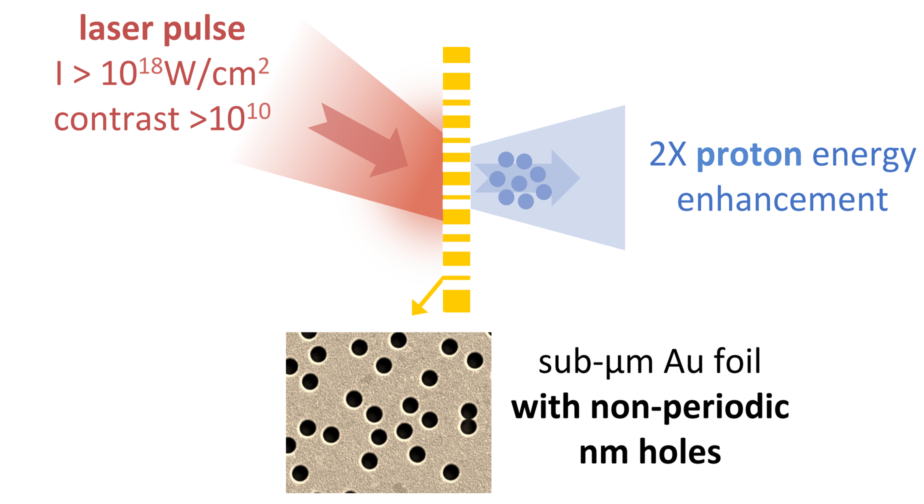
Motivation and key-concepts



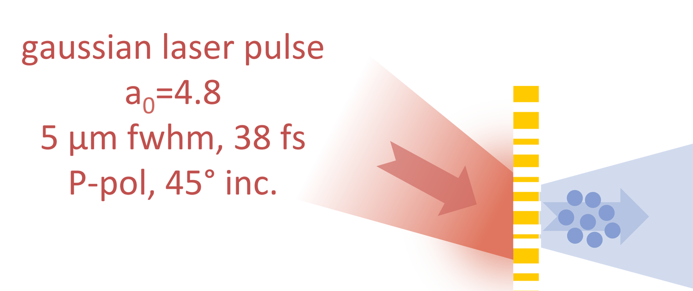
The interaction of high-power, high-contrast laser pulses with nanostructured targets is largely investigated as a possible way to increase energy absorption and aim to a more efficient proton acceleration.

Assuming that the target structures are preserved until the interaction with the ultra-intense laser pulse, crucial factors for the design and performances of these targets become the costs of manufacturing and handling, which in turn depend on the geometries and shapes dictated by the physical mechanisms at play. Reducing these costs is part of the successful development of efficient, high-repetition proton sources.

Here we present the results of our recent study on the maximum energies of TNSA-driven proton beams obtained when irradiating sub-µm foils perforated with a non-periodic distribution of nm-size holes [1].

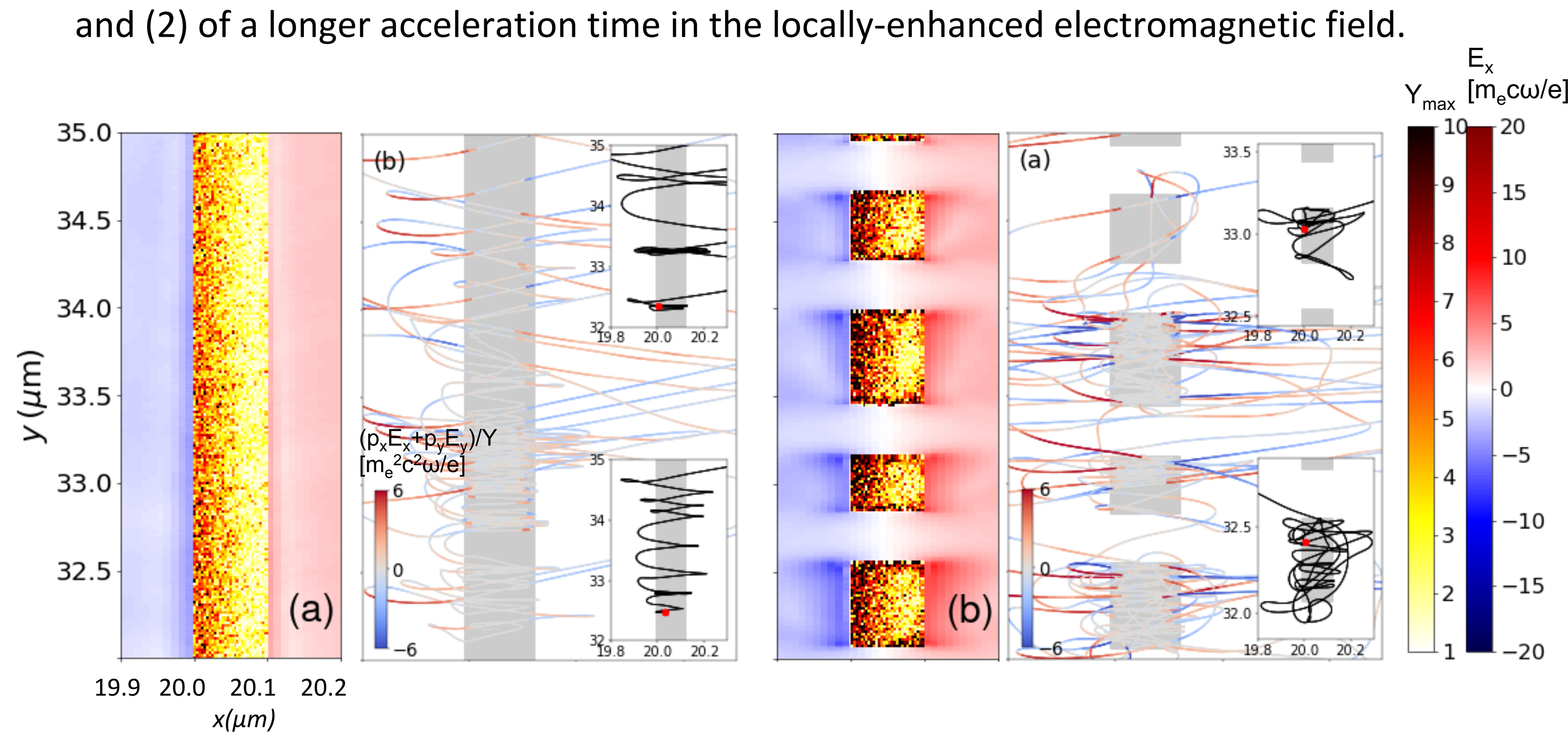
Despite numerical simulations predict a x2 energy enhancement with respect to a standard flat foil, experiments suggest that the pulse contrast routinely achieved with a double plasma mirror may not be high enough to preserve the target structuring.

2D Particle-In-Cell studies (SMILEI)

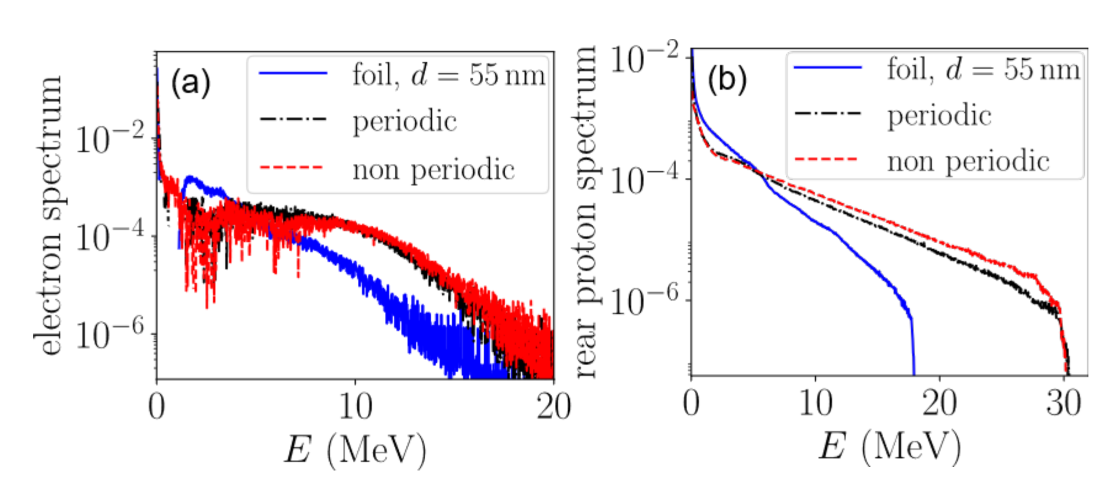


$n_{i,Au}$=6.10^{22} cm^{-3}, n_p=2.10^{23} cm^{-3}
d (target thickness) = 100 nm
b (hole diameter) = 300 nm
σ (areal hole density)= 44%
100 ppc in bulk, 1000 ppc in proton layer
δx=δy=5 nm; δt=11.7 as

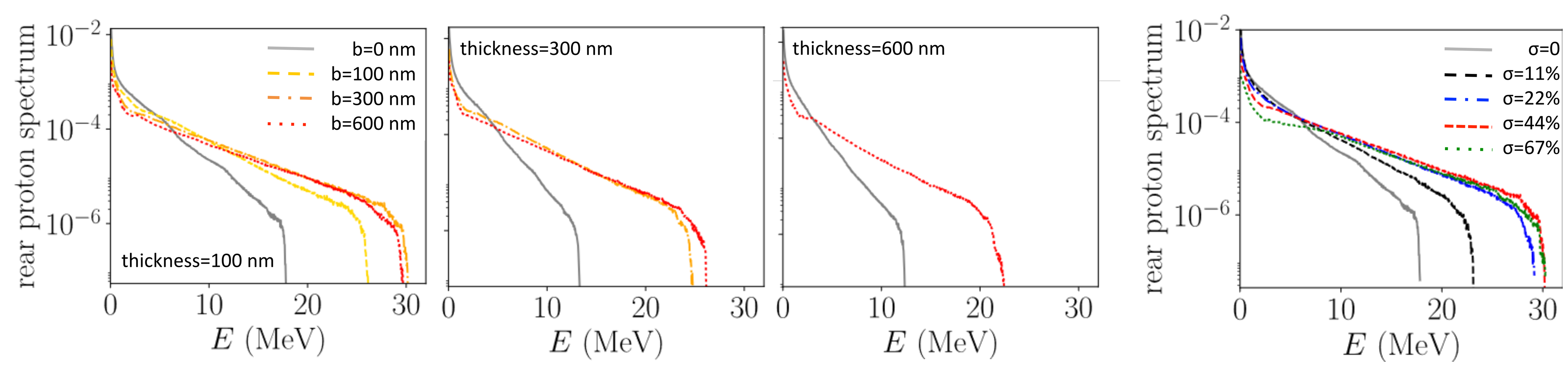
Simulations show that the target structuring increase the average electron energy because (1) of more electrons extracted from a larger area of interaction –i.e. the nanoholes walls, and (2) of a longer acceleration time in the locally-enhanced electromagnetic field.



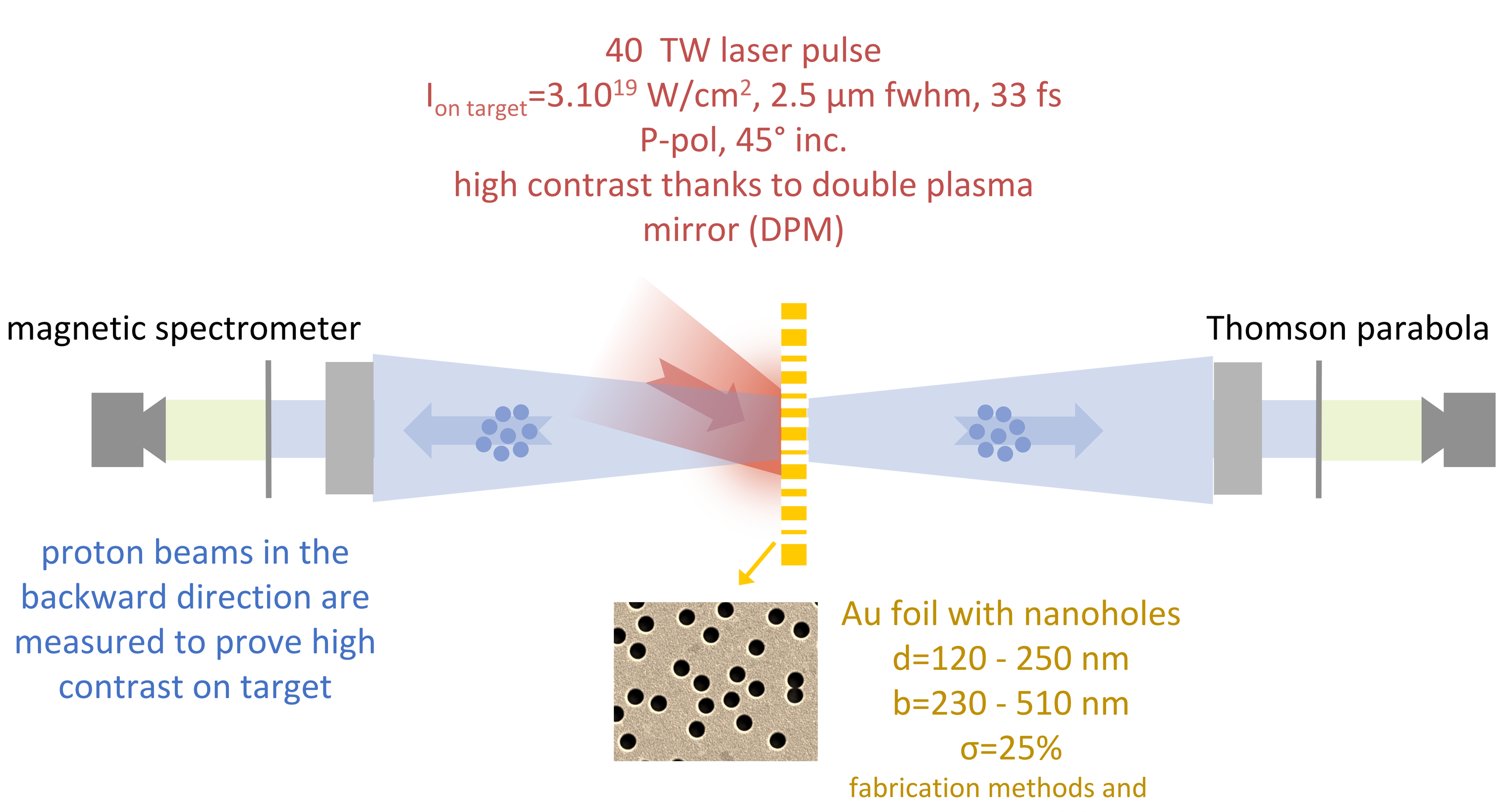
The target structuring, rather than its reduced volume with respect to a flat foil, is crucial to observe the enhancement. However, a periodic arrangement of nanoholes [2] is not essential to increase the TNSA performance, thus relieving the manufacturing constraints.



The proton energy enhancement is observed for a variety of nanoholes parameters (diameter and density). In general, very low densities could increase shot-to-shot fluctuations in case of small laser focal spots. Larger holes reduce the risks of early filling up but lead to higher laser transmission. The optimal target thickness is a tradeoff between nanohole enhancement and efficient vacuum heating.

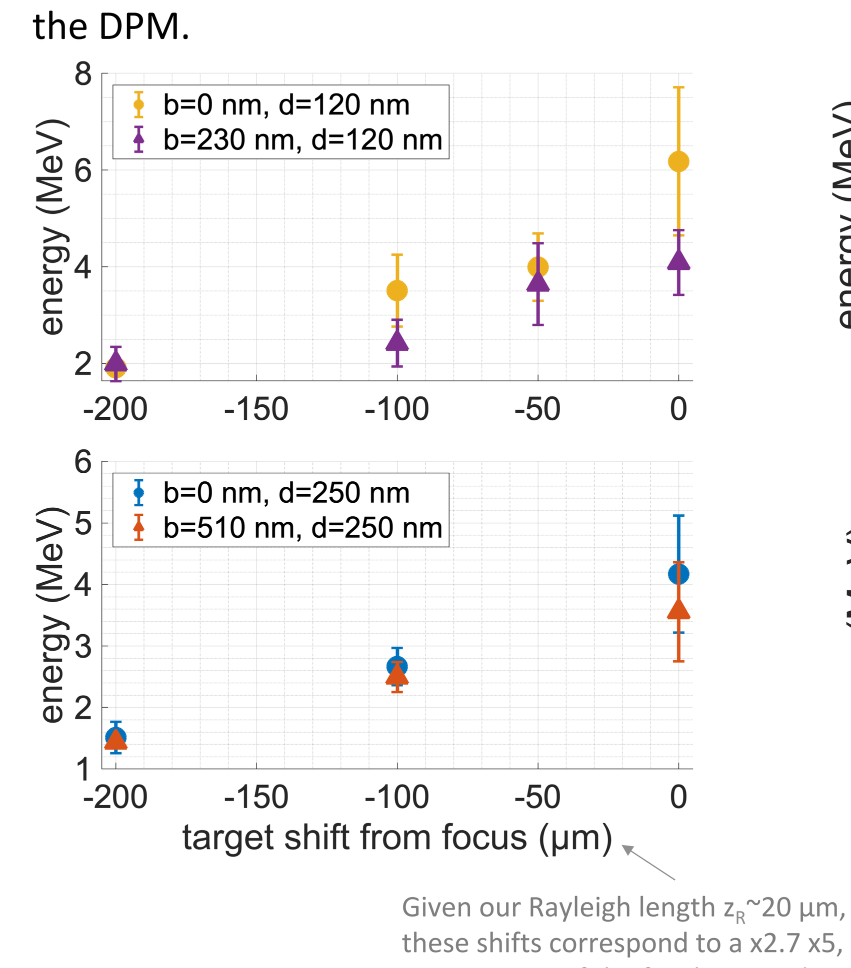


Experimental results (LLC & GU)



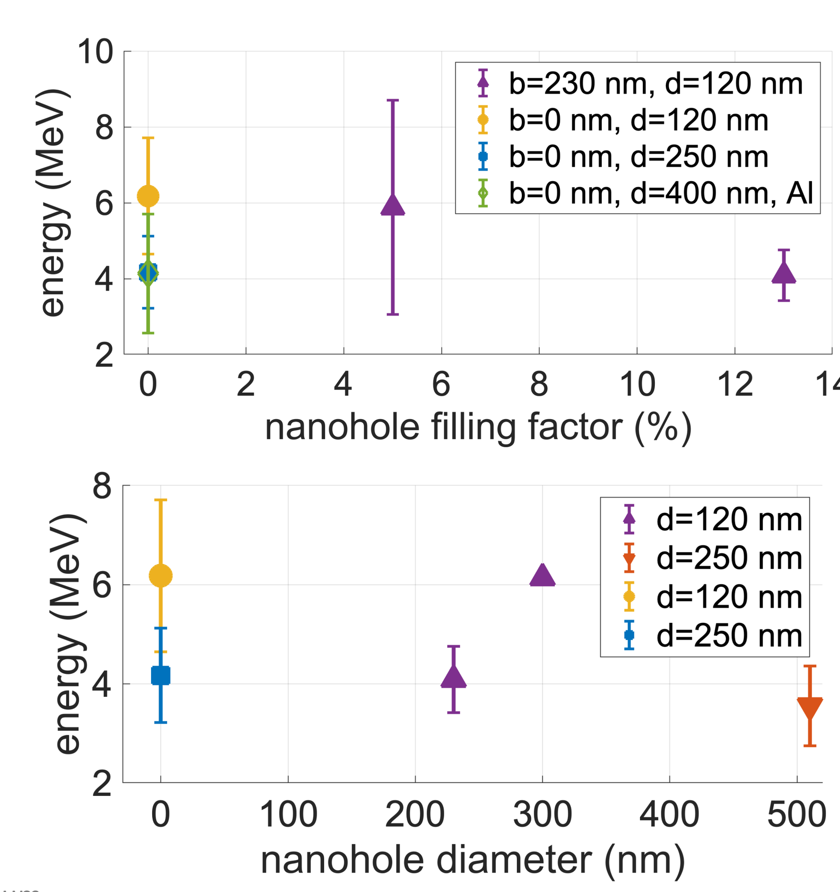
Nanohole targets fabricated at Gothenburg University have been irradiated at the Lund High Power Laser Facility. Despite testing different target parameters, we could not observe the proton energy enhancement predicted by the PIC simulations.

Moving the target away from the optimal focus increases the irradiated area without altering the behavior of the DPM.

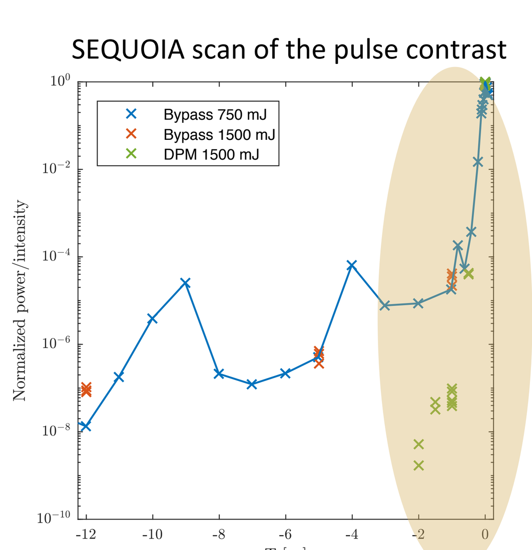


Given our Rayleigh length z_R~20 µm, these shifts correspond to a x2.7 x5, x10 increase of the focal spot radius

Increasing either the nanohole density or their diameter did not lead to higher proton energies.



Results suggest that the nanoholes fill with plasma created in the ~2 ps preceding the pulse peak, where the DPM is ineffective.



Gold ionizes above ~10^{13} W/cm^2, reaching the critical density at 100 nm (nanohole radius) with a scale length L=30 nm (assuming Z_{Au}=1, exponential profile).

The actual scale length depends on the expansion velocity of the plasma, which is set by the energy deposited on target. Using a time-independent value for the expansion velocity in experimental conditions similar to ours [4], gives a rough estimation of L<100 nm. However, ongoing PIC simulations reveal that intense irradiation even in the few 100s of fs before the pulse peak is enough to suppress the nanoholes enhancement.

[1] Thiele et al., arXiv:1905.11131 [physics.plasm-ph], submitted to JPP (2019)
[2] Psikal et al., Phys. of Plasmas 23, 123121 (2016)
[3] Fredriksson et al., Adv. Mater. Comm. 19, 4297-4302 (2007)
[4] Flacco et al., Phys. Rev. E 81, 036405 (2010)