# *Picosecond ramp of ultrashort laser pulse: How it affects laser-driven ion acceleration and plasma shutter?*


J. Psikal[1,2] *et al.*

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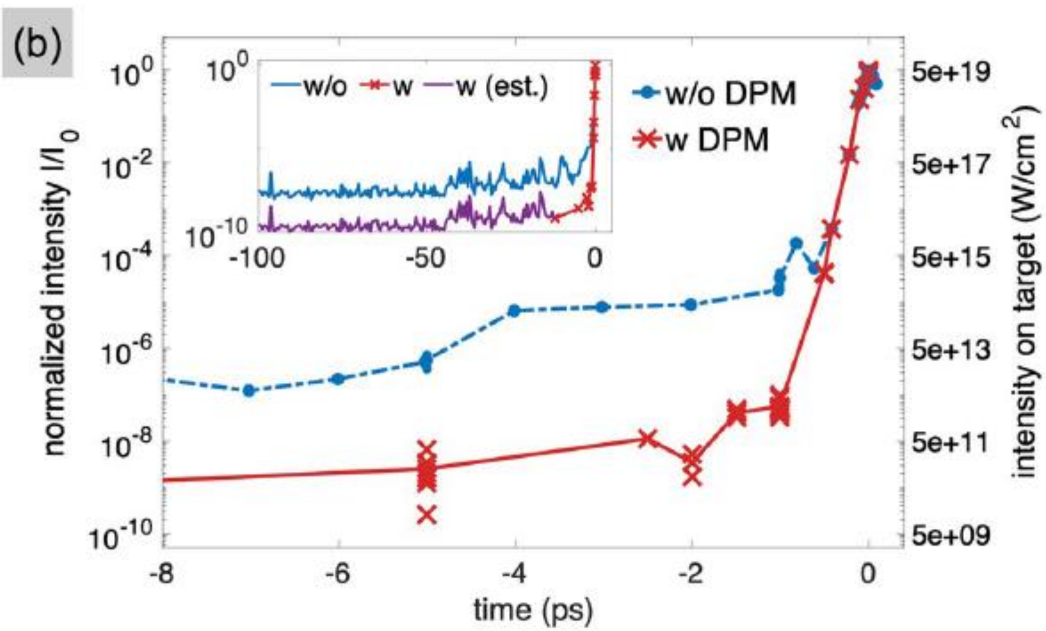
# Real temporal profile of ultrashort laser pulses

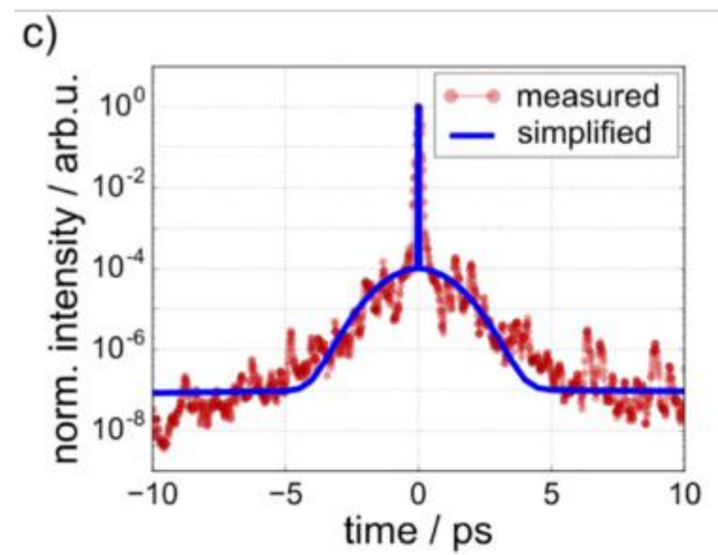
- enhancement of laser pulse contrast – (double) plasma mirror ((D)PM)
- (D)PM substantially improves laser pulse contrast, but picosecond ramp cannot be completely removed

*Example of laser pulse temporal profile with/without using DPM*




G. Cantono *et al.,* Sci. Rep. **11**, 5006 (2021)

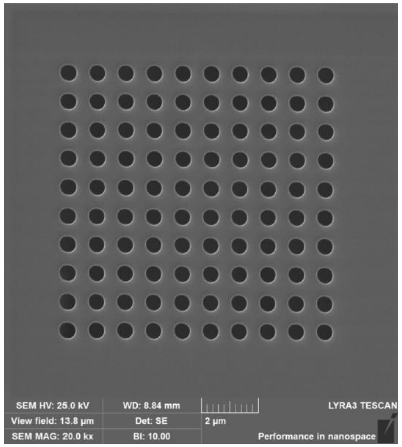
*Example of laser pulse temporal profile after using PM*




L. Obst *et al.,* PPCF **60**, 054007 (2018)

B. H. Shaw *et al.,* PoP **23**, 063118 (2016)

# Effects of short ps ramp in experiments

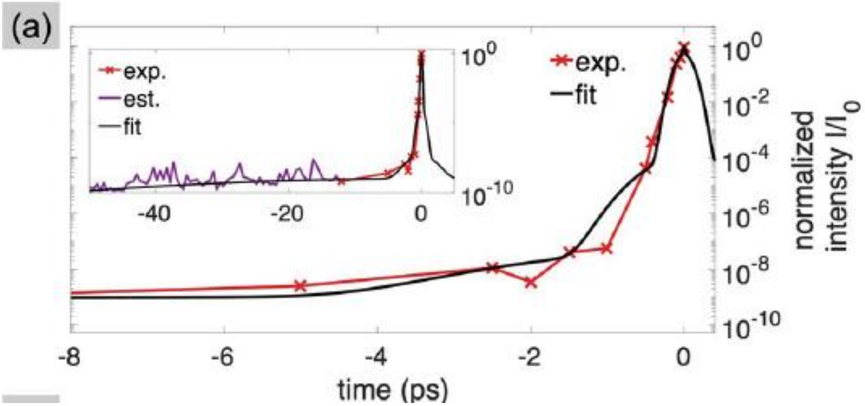


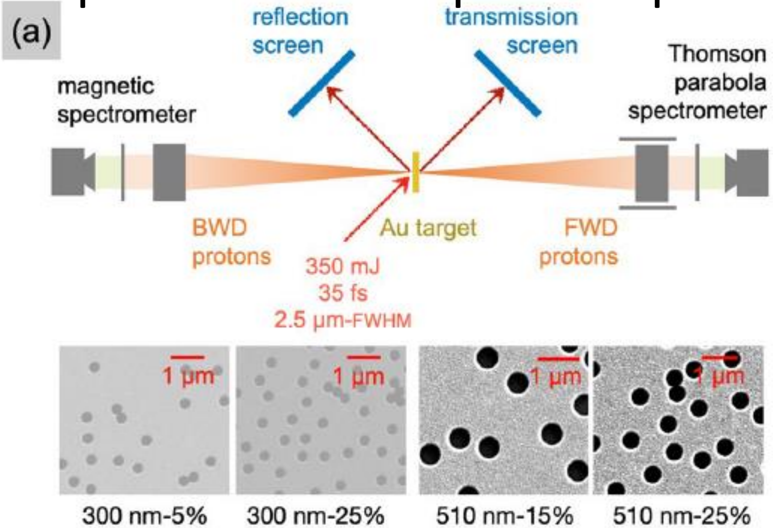

- enhancement of max. ion energies predicted by numerical simulations with ultrashort pulses when targets with nanoholes are irradiated by the pulses

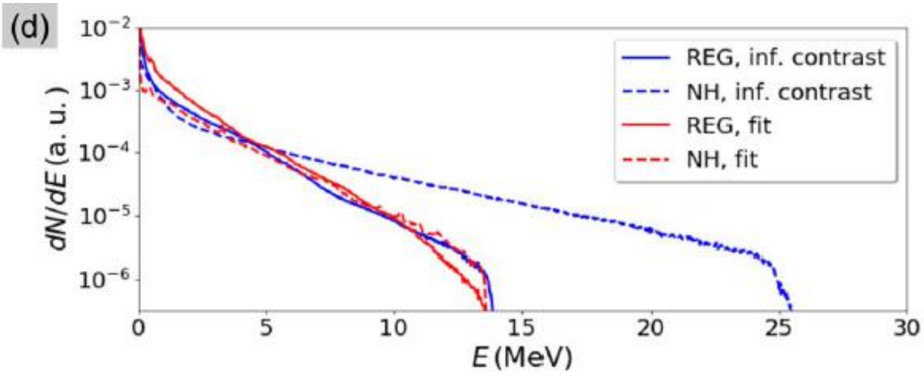
  Y. Nodera *et al.,* PRE **78**, 046401 (2008)

  J. Psikal *et al.,* PoP **23**, 123121 (2016)

- this enhancement has not been observed in any experiment and later in the simulation taking into account picosecond ramp of the pulse




G. Cantono *et al.,* Sci. Rep. **11**, 5006 (2021)

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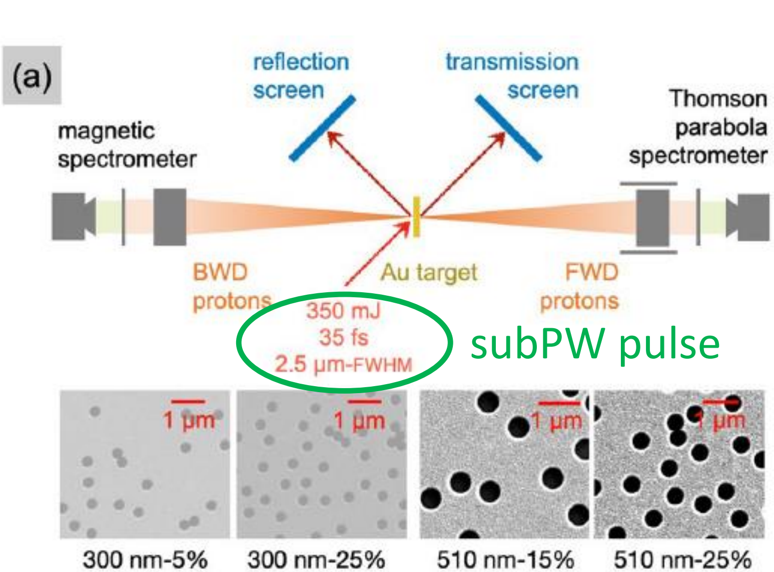
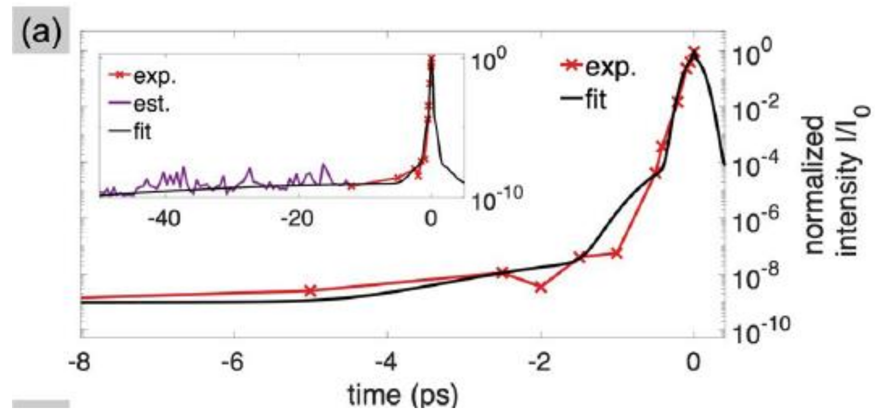
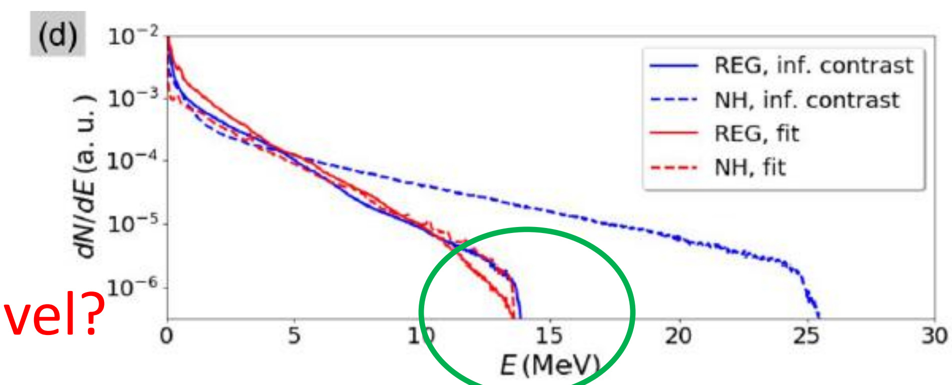



G. Cantono *et al.*, Sci. Rep. **11**, 5006 (2021)

What can happen at PW pulse level?

# Particle-in-cell simulations with picosecond ramp of ultrashort pulse

- collisions should be included (?)
- computationally more demanding as the interaction time is longer and laser intensities lower (for picosecond ramp) => smaller sizes of cells, much more timesteps in the simulation=> 3D simulations are not feasible

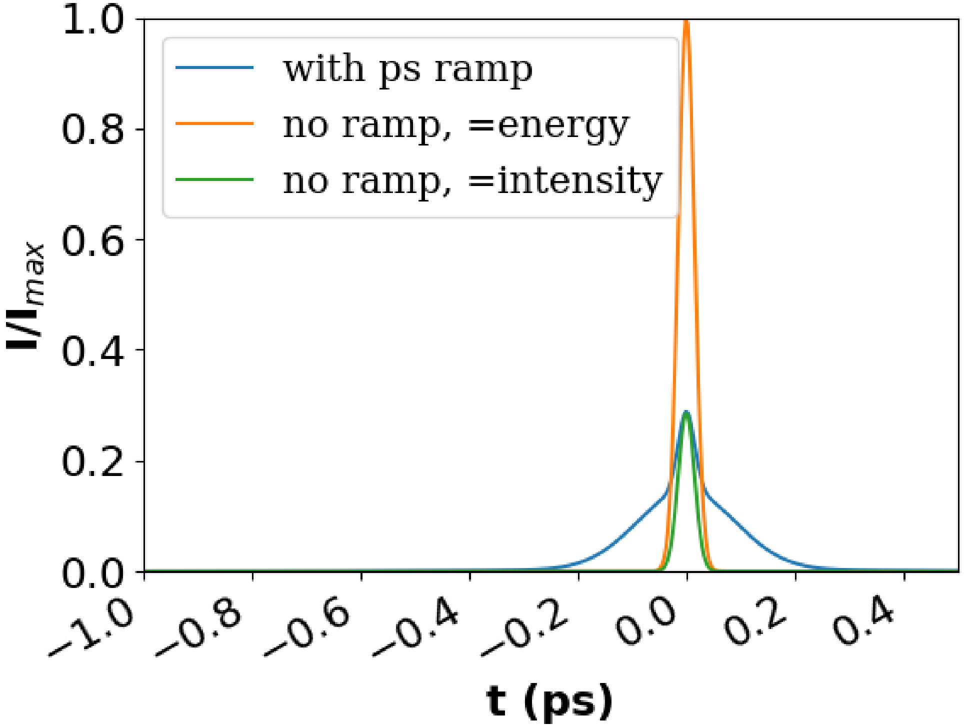
Smilei)

J. Derouillat *et al.,* Comp. Phys. Comm. **222**, 351 (2018)

- 2D PIC simulations including collisions ran approx. twice longer compared with collisionless simulations
- a huge number of particles concentrated in a small part of the whole simulation box => less sophisticated linearized decomposition to rectangular areas (narrow stripes) used for relatively efficient parallelization

# Temporal profiles of laser pulses in our simulations

1) ultrashort pulse with picosecond ramp
2) clean ultrashort pulse of the same energy
3) clean ultrashort pulse of the same peak intensity




$I_{max} = 10^{19} - 10^{21}$ W/cm$^2$

$\tau_{FWHM} = 35$ fs

$I/I_{max} = [\Sigma A_i * \exp(-t^2/(2\sigma_i^2))]^2$

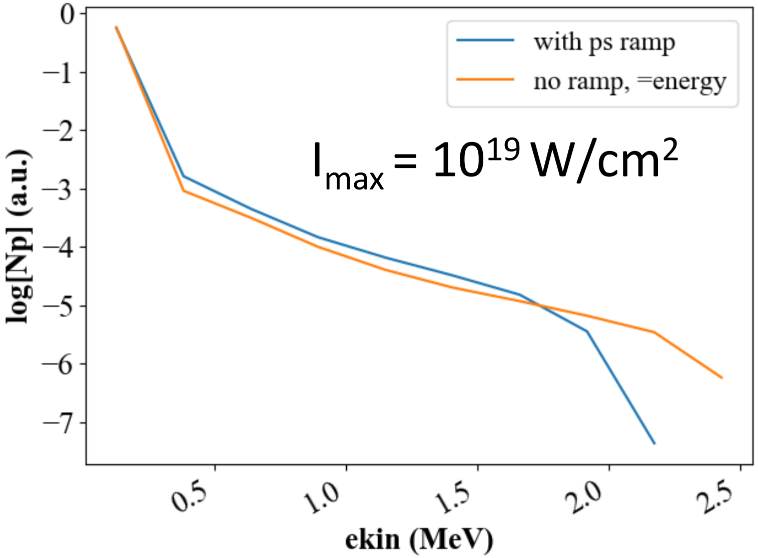
A1=0.5; A2=0.5; A3=0.01;

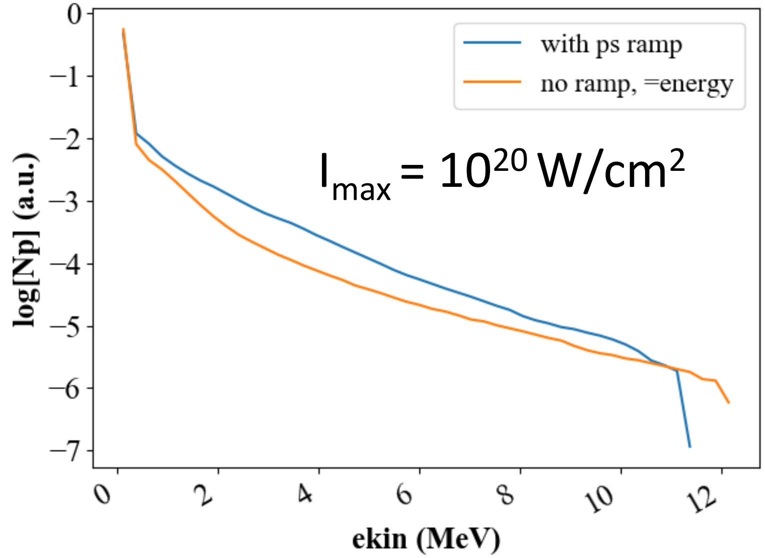
$\sigma_1$=15 fs; $\sigma_2$=90 fs; $\sigma_3$=350 fs

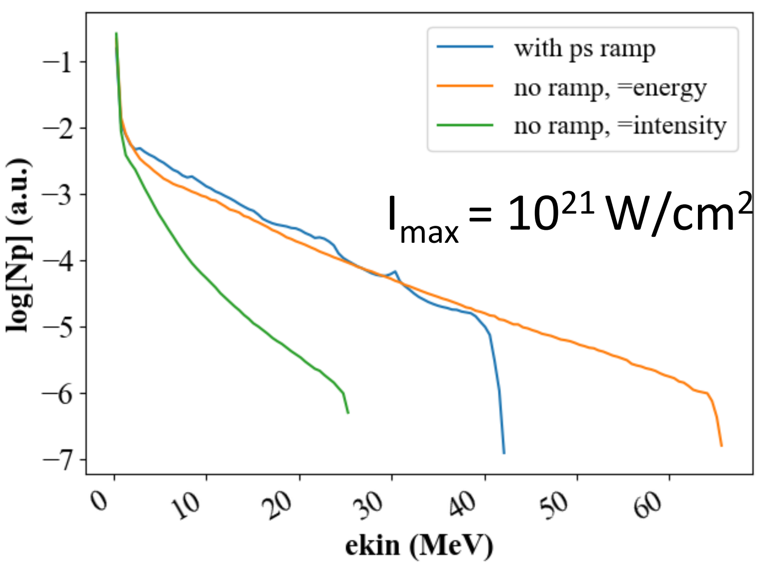
$A_i$ and $\sigma_i$ values taken from

G. Cantono *et al.,* Sci. Rep. **11**, 5006 (2021)

# Effect of picosecond ramp on TNSA



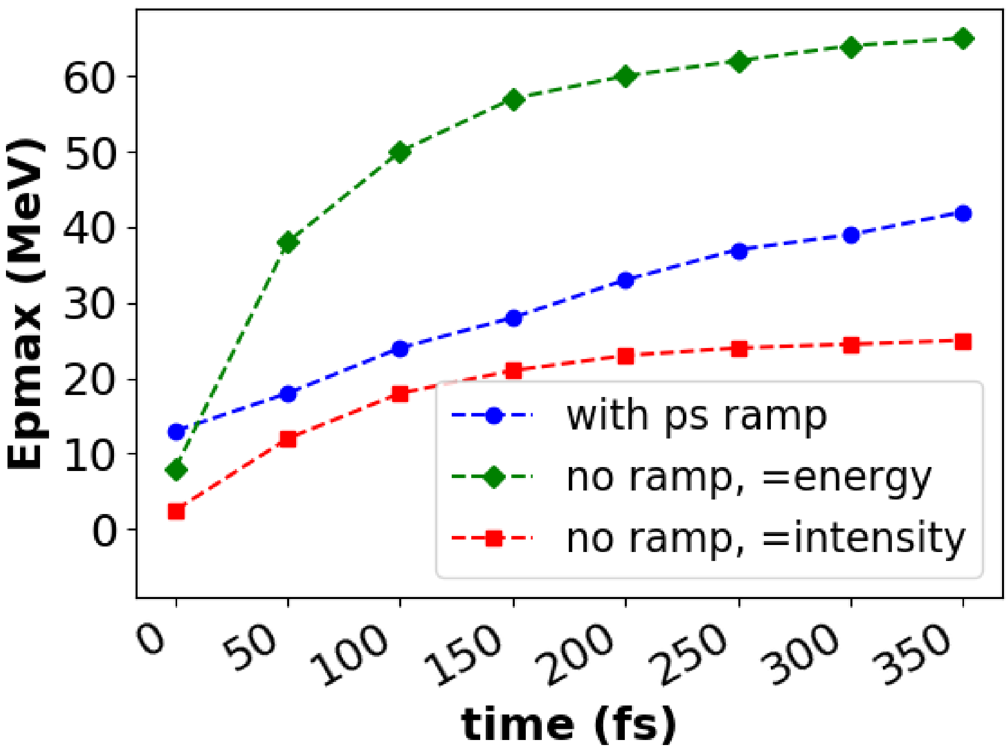




- interaction of the pulses with 1 µm thick hydrogen target of density 50 $n_{ec}$, irradiated at 15°, collisions included
- **max. (cutoff) energies of accelerated protons** are very similar at peak pulse intensities below $10^{21}$ W/cm$^2$, they **substantially differ at $10^{21}$ W/cm$^2$**

# Ion acceleration during pulses interaction with the target (peak intensity $10^{21}$ W/cm$^2$)

- most of the acceleration happens during short period of the interaction in the case of clean ultrashort pulses
- when ps ramp is present, ions are accelerated earlier to higher energies but the acceleration is less efficient when peak intensity interacts with the target

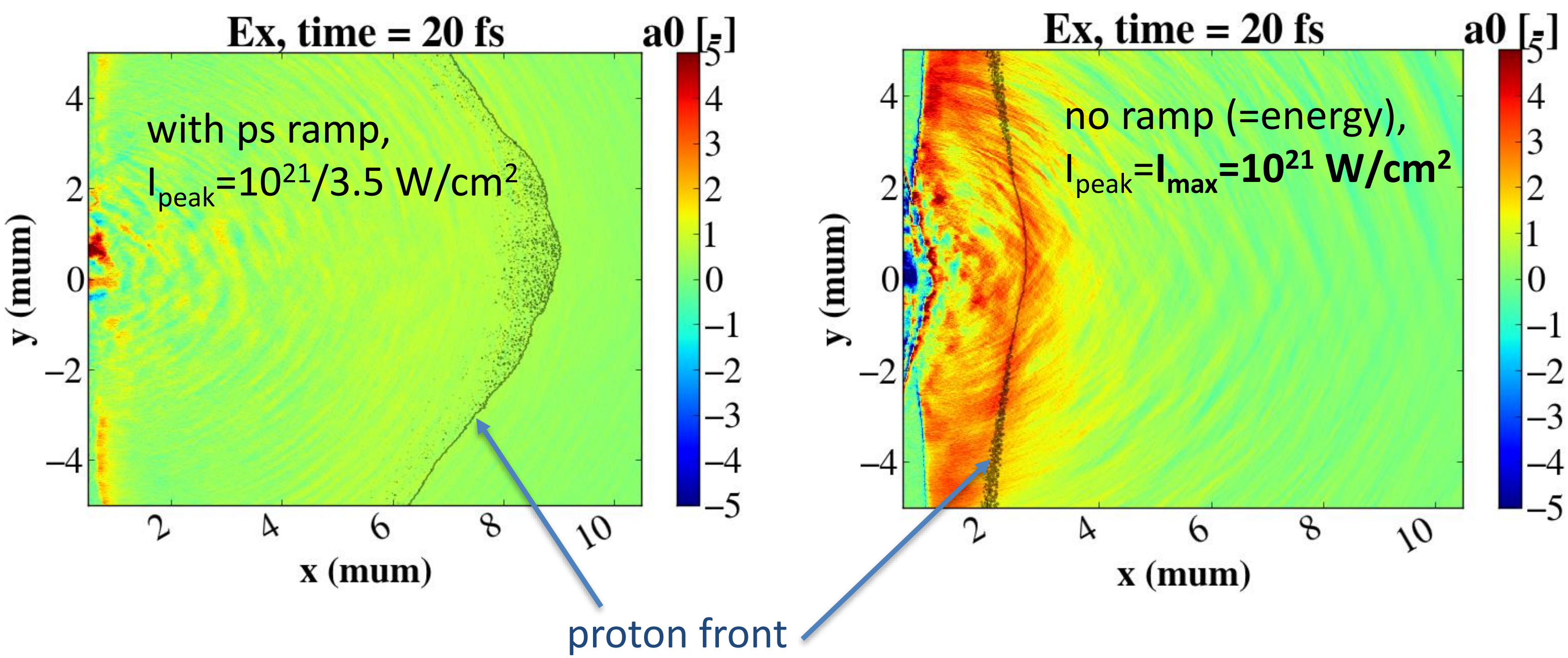



- later, the difference between the clean pulse and the pulse including ps ramp is reduced as the ramp after the main pulse still interacts with the target

*temporal evolution of max. energies of accelerated protons, **peak** pulse **intensity** interacts **at t=0***

# Target expansion and accelerating fields

- target expansion leads to reduced accelerating fields after the interaction with peak pulse intensity when picosecond ramp is present

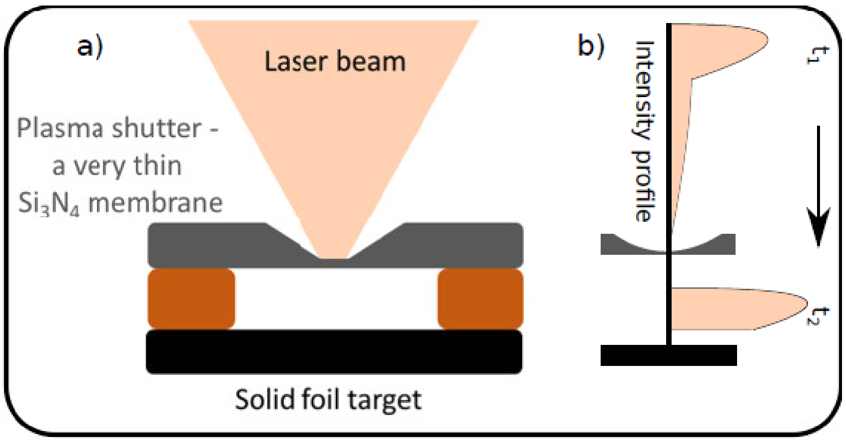



*longitudinal electric fields in the centre of simulation region, front side of 1 µm thick target at x=0, black curve depicts front of accelerated protons*

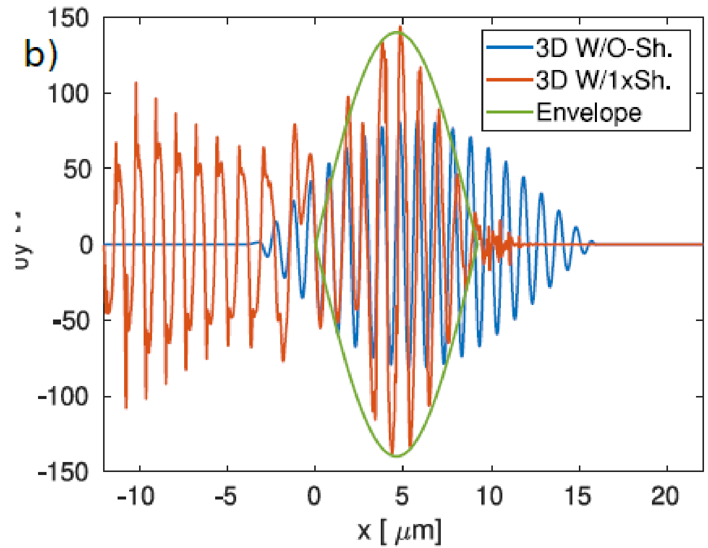
- at $I_{max}$<=$10^{20}$ W/cm$^2$ pre-expansion is less pronounced => similar cutoff energies for both cases

# Plasma shutter and picosecond ramp

- plasma shutter = ultrathin solid foil (membrane) which can filter out low intensity parts of the laser pulse and make the pulse front steeper




M. Matys *et al.*, New J. Phys., submitted (2022)




- the shutter can also enhance peak pulse intensity

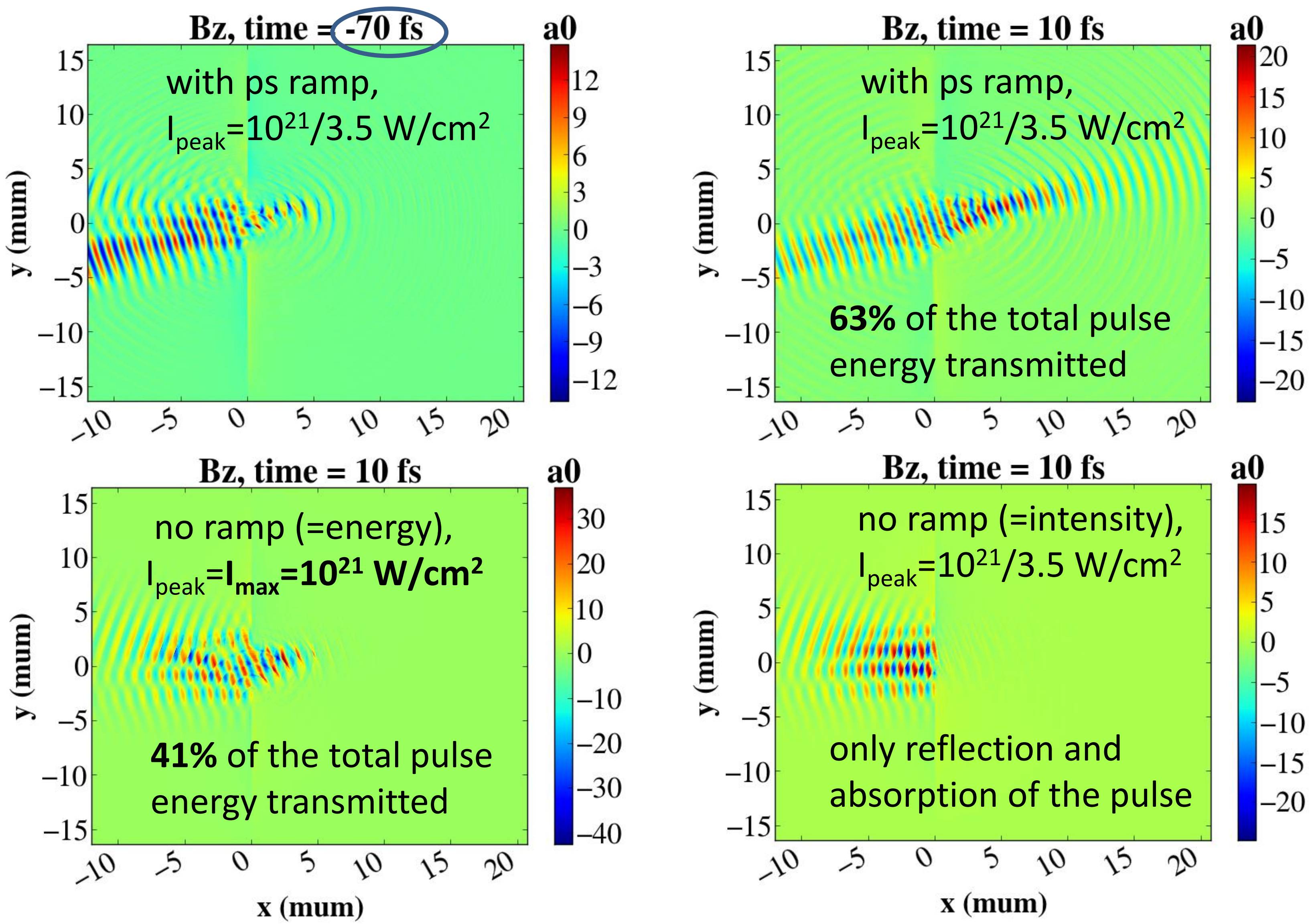
M. Jirka *et al.*, Phys. Rev. Res. **3**, 033175 (2021)

- thickness of the shutter should be comparable to the value when laser pulse is able to push all electrons away from the foil by the radiation pressure

$$l = (a_0\, n_c\, \lambda) / (\pi\, n_e)$$

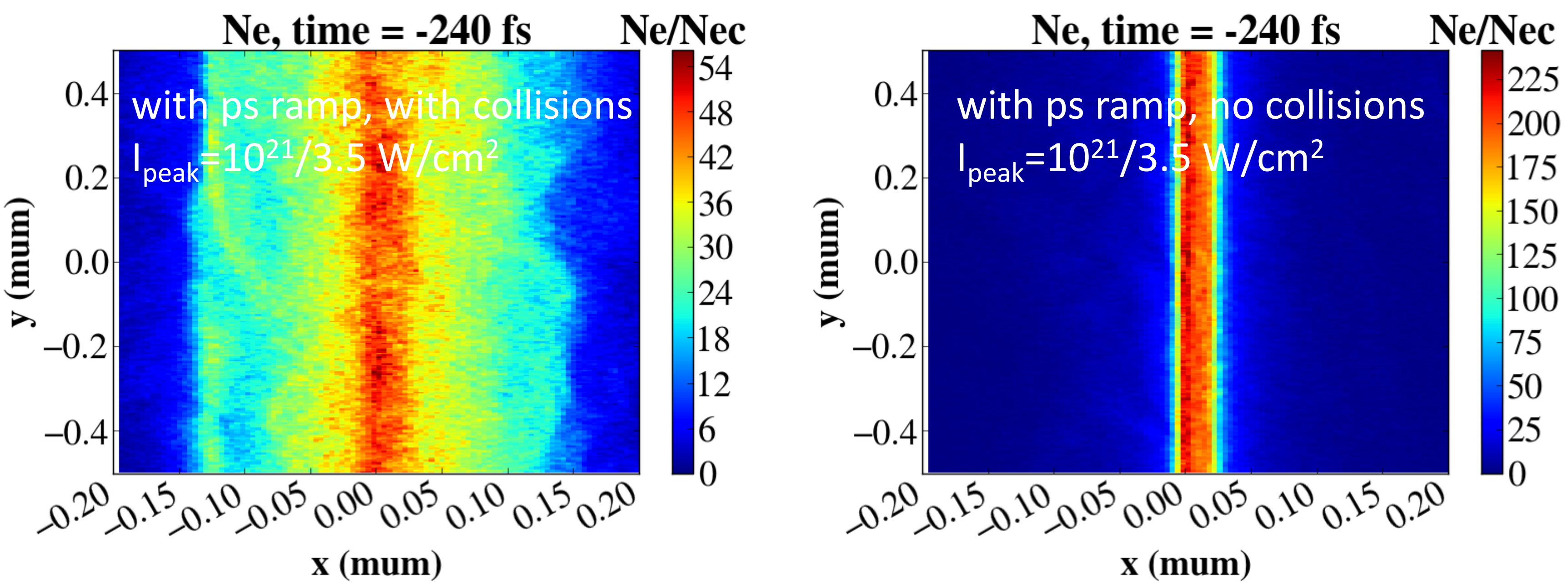
≈ 10 nm - 20 nm $Si_3N_4$ for intensities relevant to PW pulses

# Effect of ps ramp on laser pulse transmission through 12 nm thick $Si_3N_4$ plasma shutter



# Collisions in the simulations with picosecond ramp

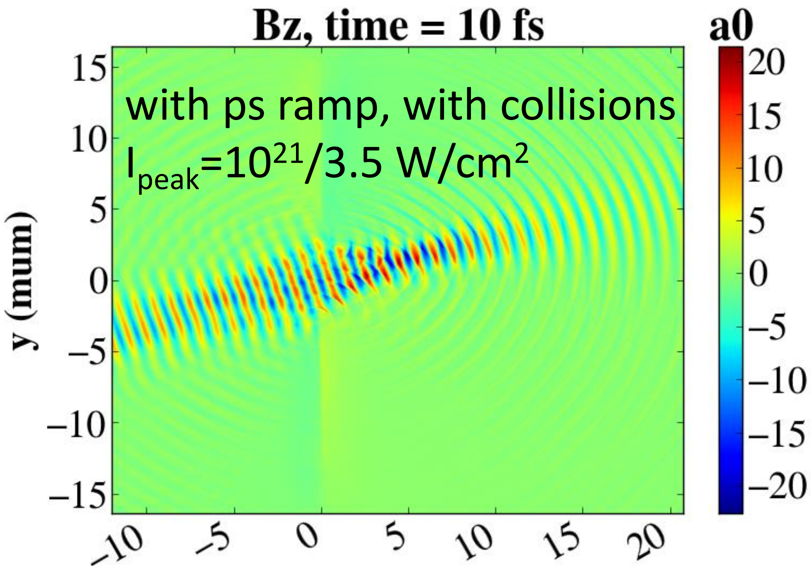
- comparison of PIC simulations with/without collisions between electrons and electron-ion collisions – ***plasma shutter***

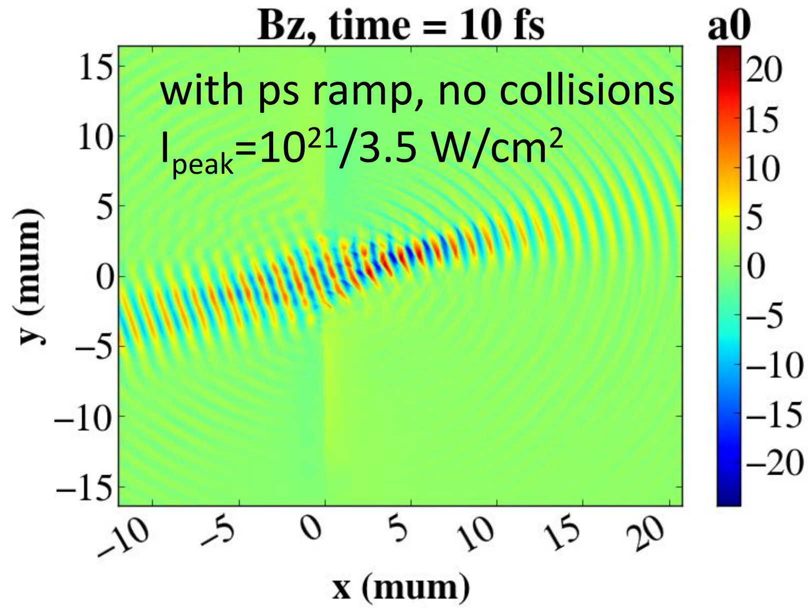


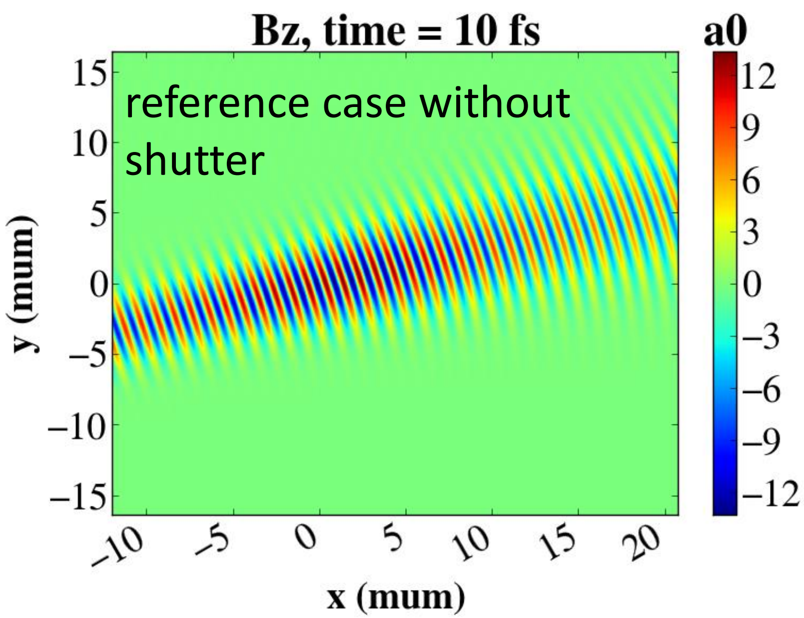

*electron densities in the centre of simulation region, front side of 12 μm thick $Si_3N_4$ membrane initially at x=0, electron density* ***Ne0=835*Nec*** *in the beginning of simulations*

- earlier stage of interaction - collisional absorption dominates (lower intensities)
- but we cannot see any substantial difference about 100 fs later when more intense part of ps ramp interacts with the target

# Comparison between collisional/collisionless simulations of laser pulse transmission through plasma shutter




- 63% of laser pulse energy transmitted through plasma shutter (difference between collisional and collisionless case below 1%)
- enhancement of the amplitude of laser pulse transmitted through the shutter (focusing)

# Conclusions

- picosecond ramp of ultrashort pulse cannot be completely removed by plasma mirrors, it can affect experimental results in some cases
- maximum energies of laser-accelerated ions can be reduced due to the interaction of picosecond ramp with thin foils and the following target expansion before the main ultrashort pulse (at intensities relevant for PW lasers) => important effect with increasing pulse power
- picosecond ramp changes the performance of plasma shutter => thicker shutter needed to filter out the whole ramp (12 nm => 24 nm in our case; 63% => 29% of the total pulse energy transmitted)
- collisions included in PIC simulations are not necessary in these studies (when picosecond ramp is relatively short and peak pulse amplitude a0>>1)