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Workshop on Particle-In-Cell simulations for laser - plasma interaction

# High Intensity Laser-Plasma Grating Interaction: Surface Wave Excitation and Particle Acceleration



19/11/2012



## CONTEXT & OBJECTIVES

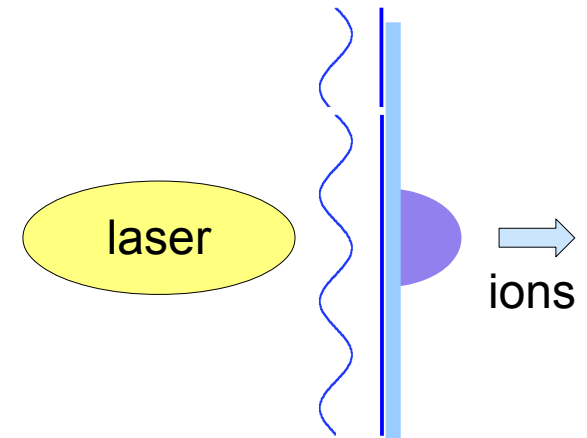
- High-intensity laser-plasma interaction  
 $I > 10^{18} \text{W/cm}^2$
- Short laser pulses  $< 100 \text{ fs}$
- High plasma density  $\gg n_c$   
( $\lambda = 1 \mu\text{m} \rightarrow n_c \sim 10^{21} \text{cm}^{-3}$ ).

### SURFACE WAVE :

- + Enhance laser absorption.
- + Enhance the production of high energy particles : electrons/ions.
- + Possibility to control the direction and parameters of the particle beams.

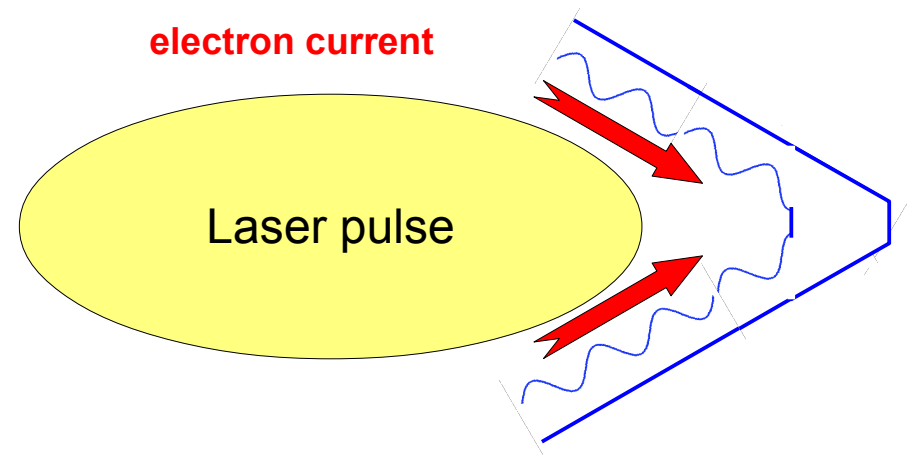
# APPLICATIONS

- + Acceleration of higher energy ions from a laminar target
- Possible application: **proton-therapy**, cancer treatment.



- + Production of hot electron beams whose parameters can be controlled :
- **Inertial confinement fusion applications : fast ignitor.**

! Electrons are emitted in the **direction of propagation of the wave, i.e. along the target surface.**



## OUTLOOK

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- Surface plasma waves (SPW) : introduction.
- PIC simulations and parametric study.
- Laser absorption via SPW : enhanced vacuum heating
- Hot electron generation.
- Ion acceleration
- Dependence on the laser pulse profile
- Conclusions



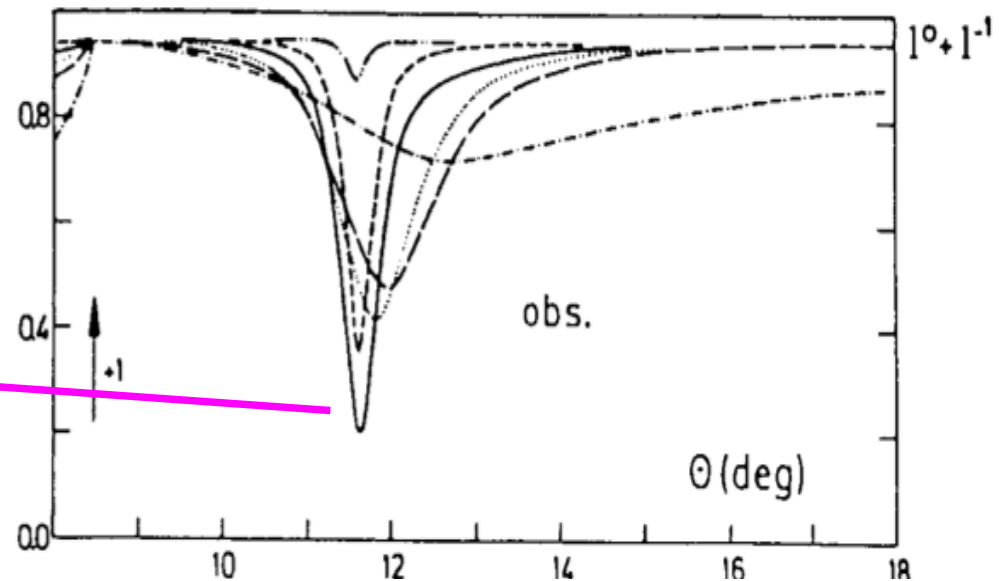
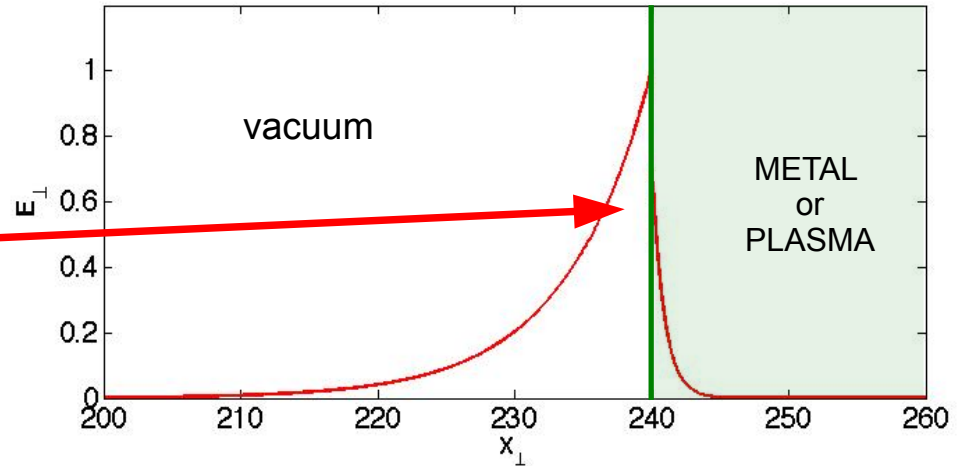
# SURFACE PLASMA WAVES (SPW)

High frequency electron wave

Localized at the interface between two media

Surface waves were first observed by Wood (1902) in the laser-metallic grating interaction.

When a surface wave is resonantly excited, we observe a peak in light absorption.



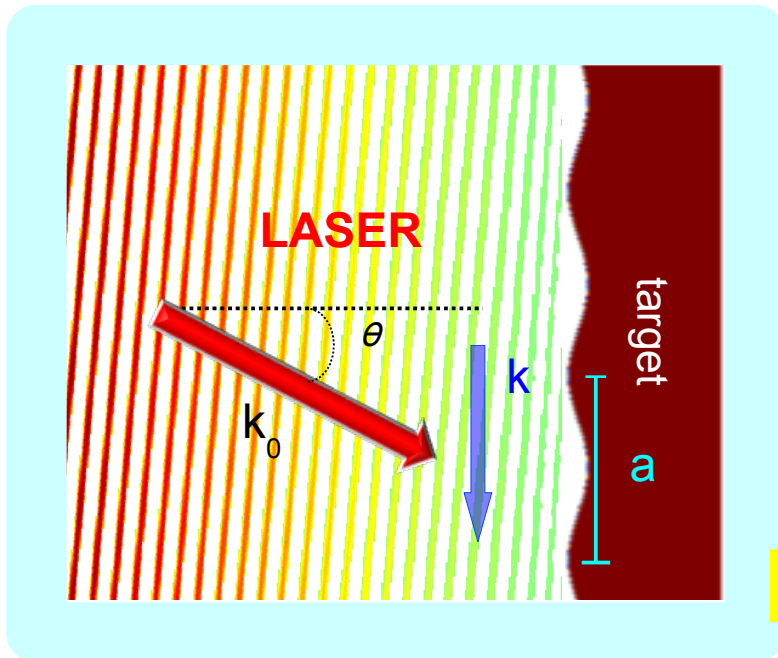
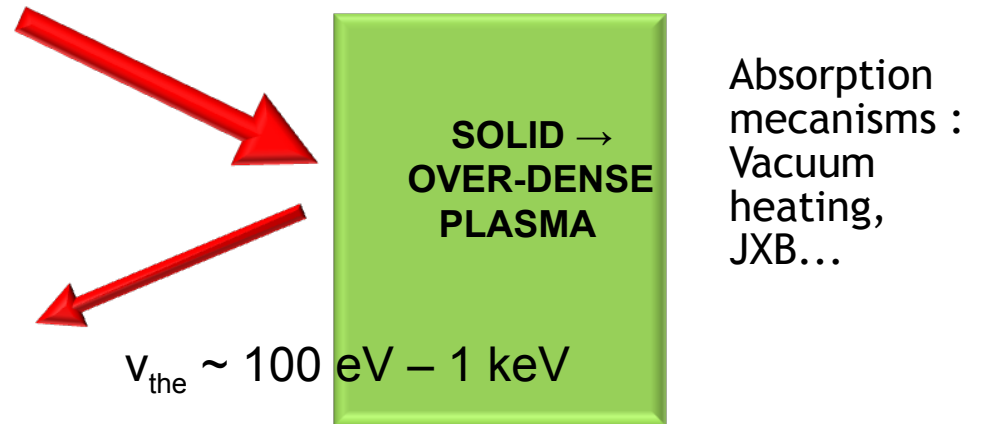


# LASER-MATTER INTERACTION

**Fast ionisation, limited hydrodynamic expansion**

For high laser intensities  $>10^{18} \text{W/cm}^2$  and ultra-short pulse duration  $< 100 \text{fs}$  :

- Generation of an overdense plasma with a steep density gradient
- **Low laser absorption** → **weak high-energy particle generation**



**IN ORDER TO INCREASE THE ABSORPTION :**

Resonant excitation of a SPW via laser-grating interaction

$$k \sim \frac{\omega}{c} \left( 1 + \frac{1}{2} \frac{n_c}{n_e} \right) \rightarrow \underline{k > k_0}$$

$$\left. \begin{array}{l} \omega = \omega_0 \\ k = k_0 \end{array} \right\} \rightarrow \text{RESONANCE CONDITION} \quad k = k_0 \sin \theta + n \frac{2\pi}{a}$$

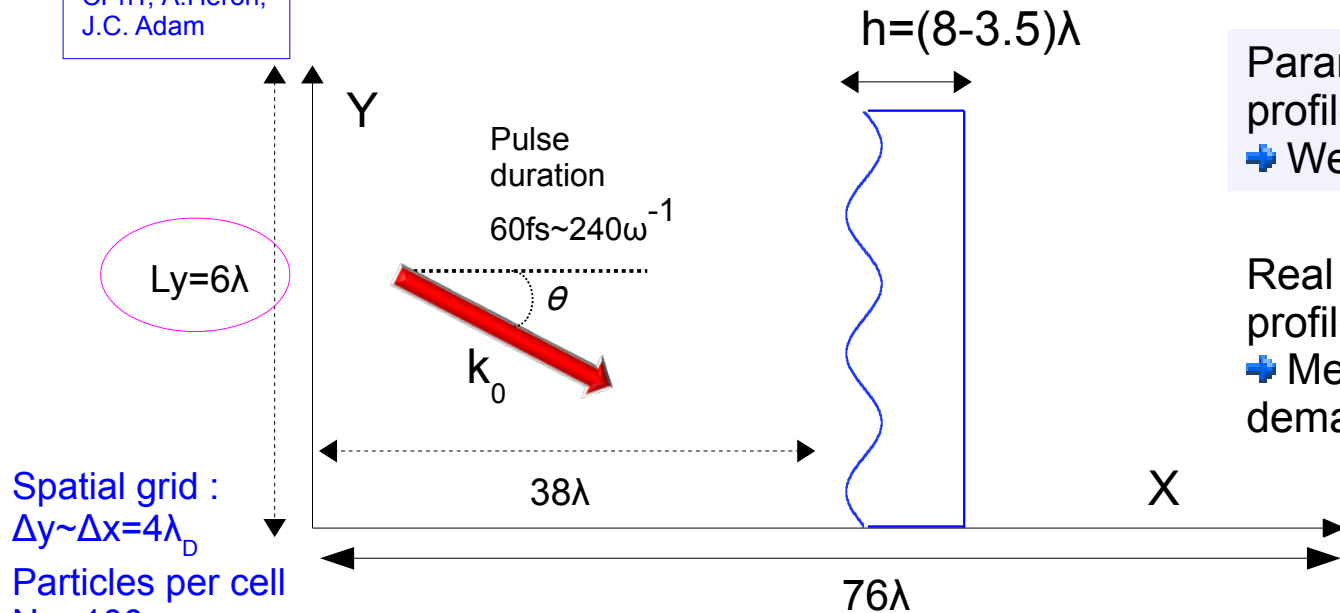
**High contrast laser pulse → the grating is not damaged**



# SIMULATION of LASER-PLASMA INTERACTION

Particle-in-cell (PIC) simulation are used to reproduce plasma dynamics and fields evolution

Code EMI2D :  
CPhT, A.Héron,  
J.C. Adam



Parametric study : uniform laser profile along y  
 + Weaker memory requirements

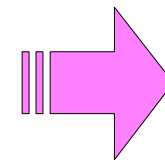
Real pulse : gaussian transverse profile.  
 + Memory requirements are more demanding

VALID DESCRIPTION

Simulation duration :  $1000\omega^{-1} \sim 0.5 \text{ ps}$  for  $\lambda=1\mu\text{m}$

Boundary conditions  
 Y → periodical  
 $Ly \sin\theta = n\lambda$   
 X → reflecting (particles)  
 / absorbing (fields)

- Laser wavelength and frequency  $\lambda_0, \omega_0$
- Grating periodicity  $a=2\lambda_0$
- Density  $n_e=25-100n_c$



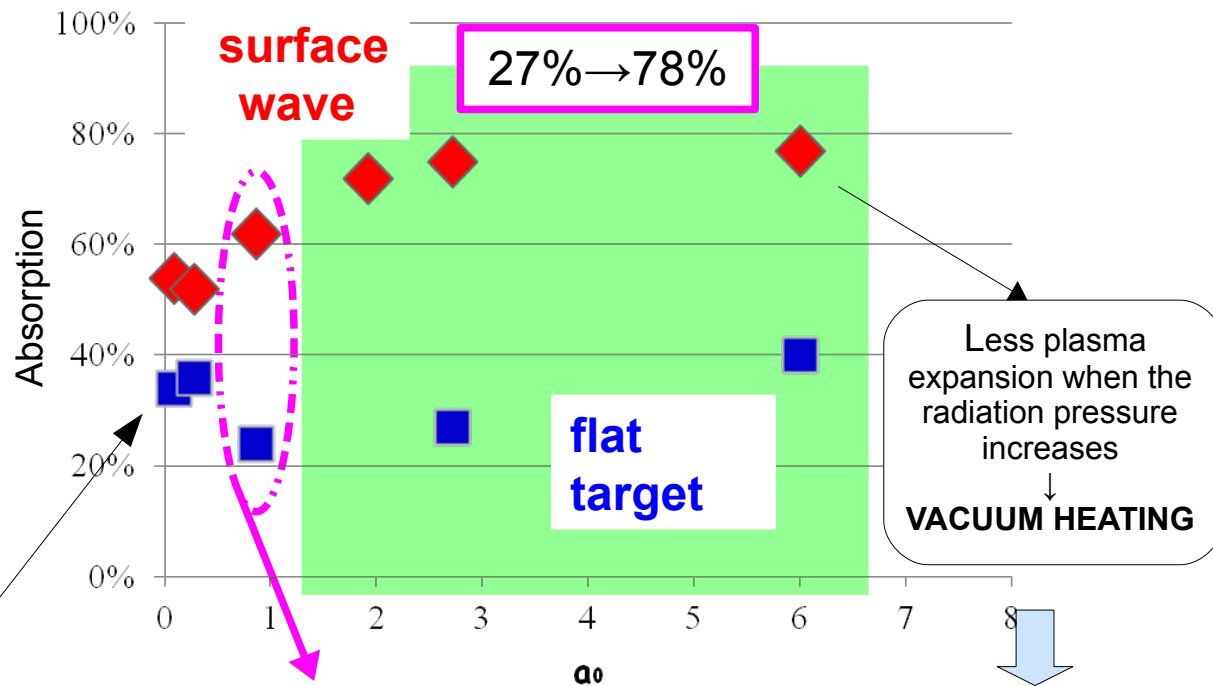
- Resonance excited for  $\theta=30^\circ$
- Wavelength and frequency of the surface wave :  $\lambda \sim \lambda_0, \omega = \omega_0$



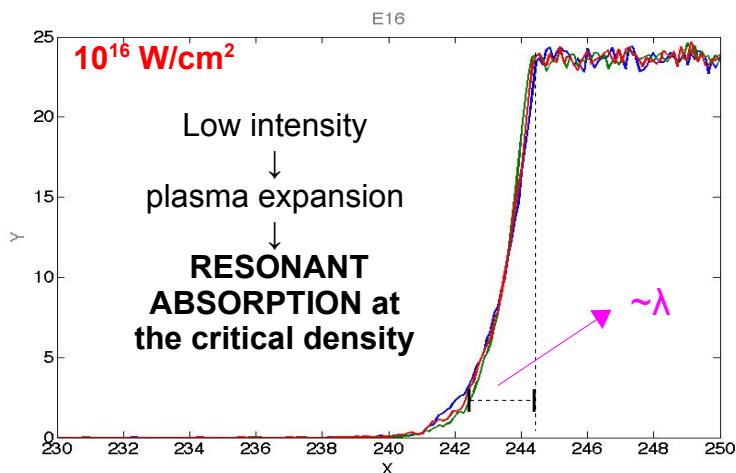
# LASER ABSORPTION

The laser absorption is enhanced when the SPW is excited

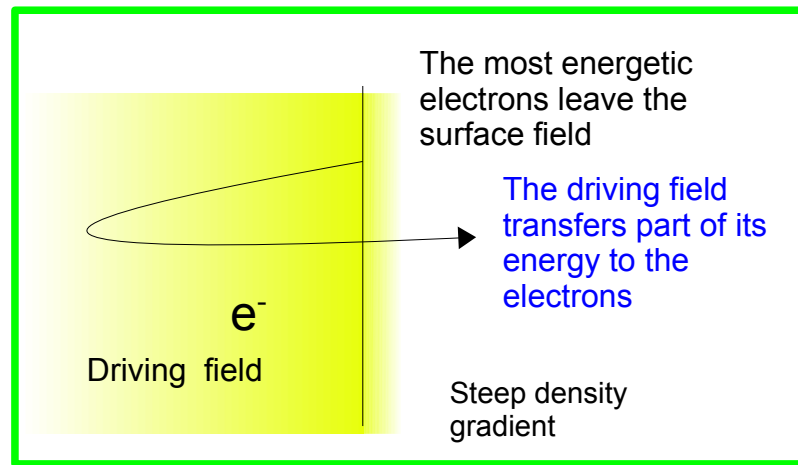
- Low intensity
- High intensity (relativistic) : **greater enhancement**



Dependence on the density gradient:



$a_0 \sim 1 : I = 10^{18} \text{ W/cm}^2$

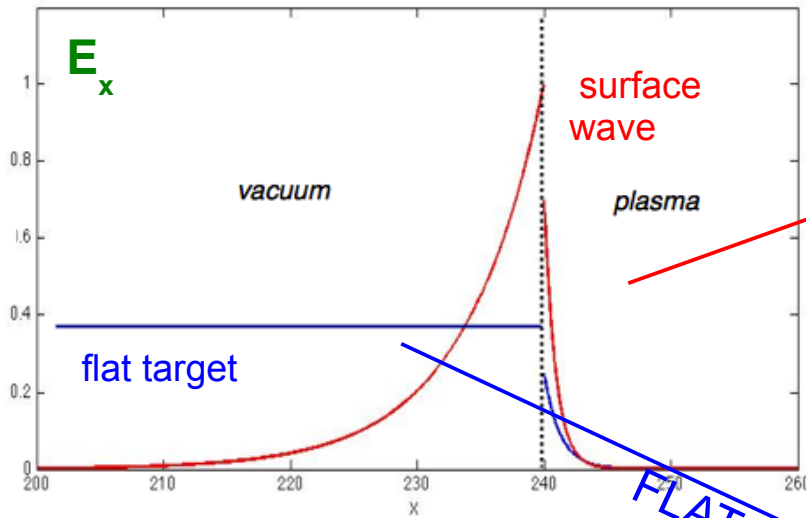






# ELECTRON HEATING

The surface wave field is more efficient in heating electrons: 'enhanced vacuum heating'



Enhanced vacuum heating : frequency  $\omega$

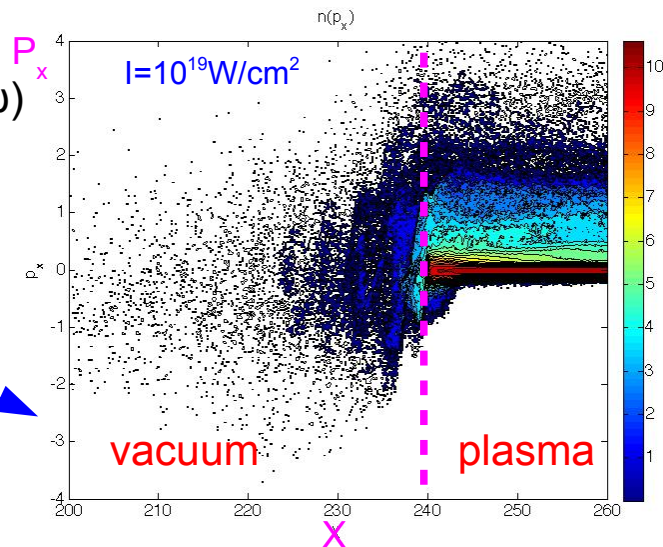
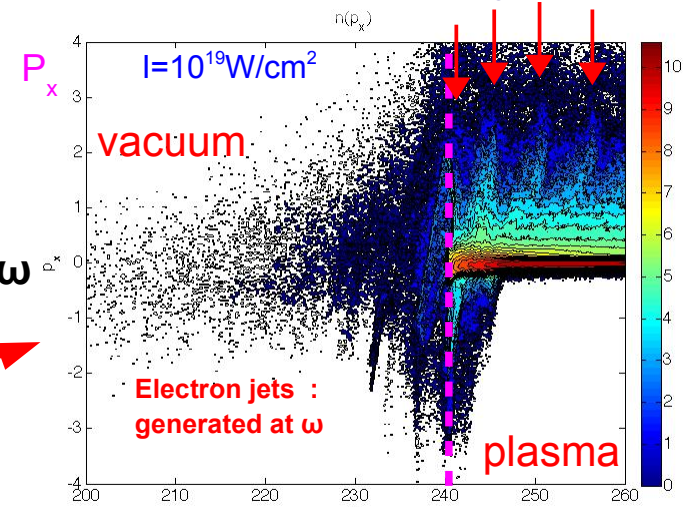
SPW

Mix of JXB (frequency  $2\omega$ ) and Vacuum heating\*  
! oblique incidence

FLAT TARGET

- Local field stronger than the laser field
- Localized field distribution : ponderomotive force towards the vacuum + restoring force
- 2D effects: e- accelerated along the surface

Momentum  $\perp$  target

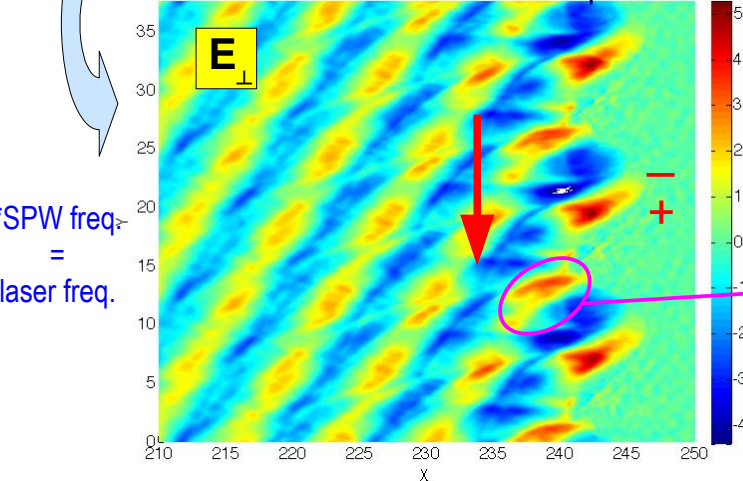
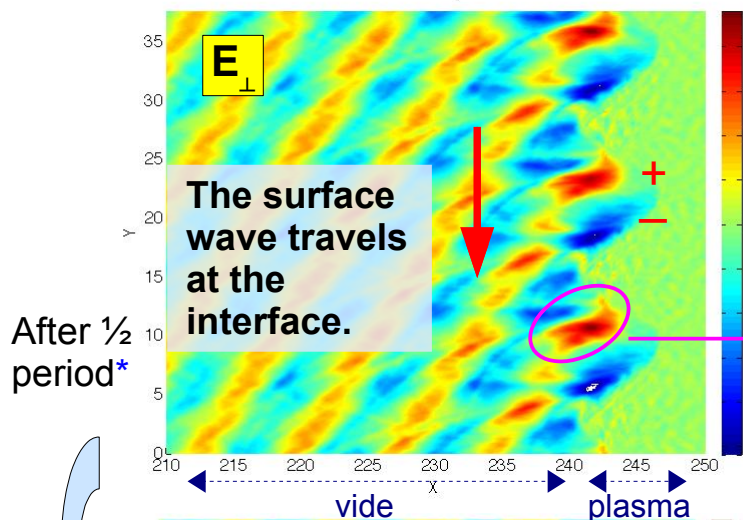




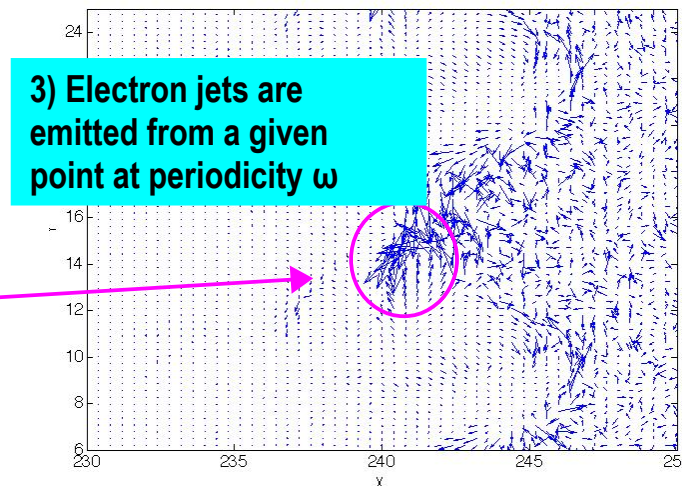
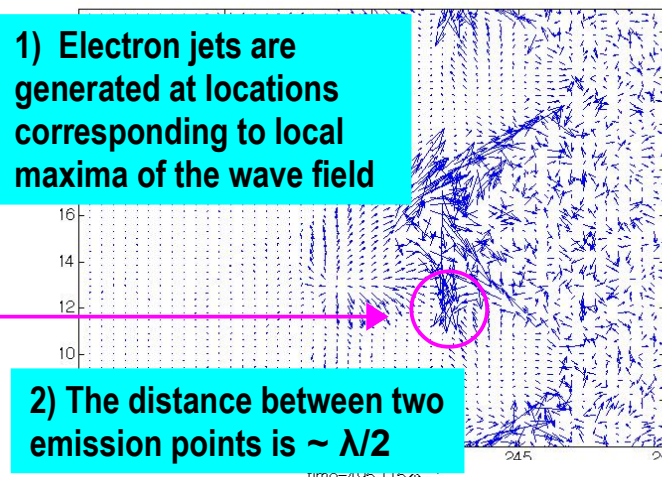
# ELECTRON JETS properties

E field at the surface :

$$t=492 \omega_0^{-1}$$



ELECTRON CURRENTS ( $\mathbf{J} = n_e \mathbf{v}_e$ )  
vector plot



The electrons experiencing the largest excursion have entered the wave field with a favourable phase and are efficiently accelerated.

If the SPW field evolves towards a:

**MAX** → electron jets, acceleration towards the vacuum

**MIN** → acceleration towards the plasma

$10^{19} \text{W/cm}^2$

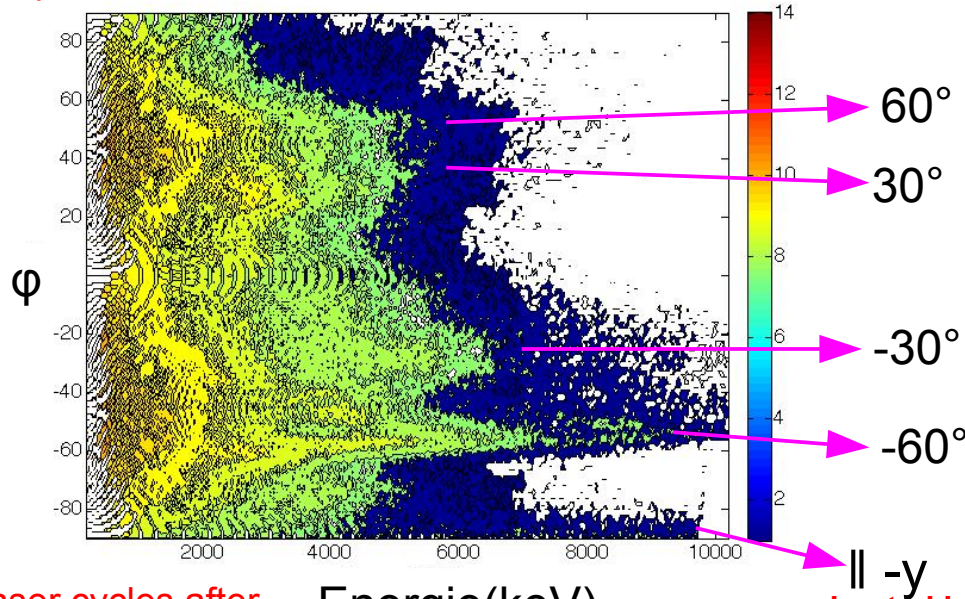


# ELECTRON ACCELERATION angular distribution

Angular distribution of the electrons accelerated towards the plasma :

$I\lambda^2 = 10^{19} \text{W/cm}^2 \mu\text{m}^2$

$n(\text{Energie}, \varphi)$



$t = 500\omega^{-1}$

~ some laser cycles after the peak pulse intensity

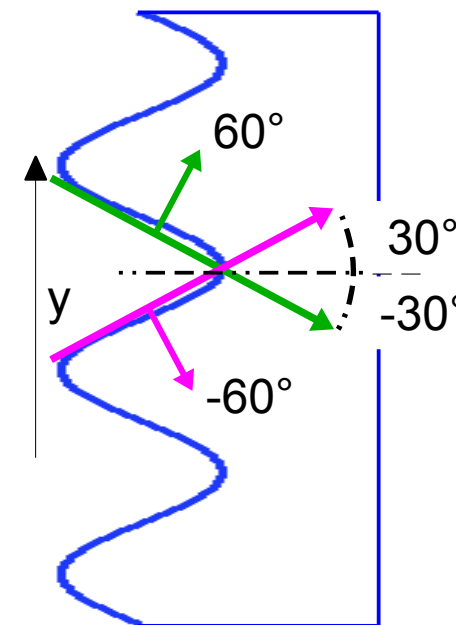
Energie(keV)

$e^-$  accelerated in the direction of propagation of the wave

Plots are obtained using the electron phase space :

$(p_x, p_y)$

The peaks correspond to the angular direction of the most energetic electrons



Geometry effects

$60^\circ$  = acceleration  $\perp$  to the target modulated surface

$30^\circ$  = acceleration  $\parallel$  to the target modulated surface

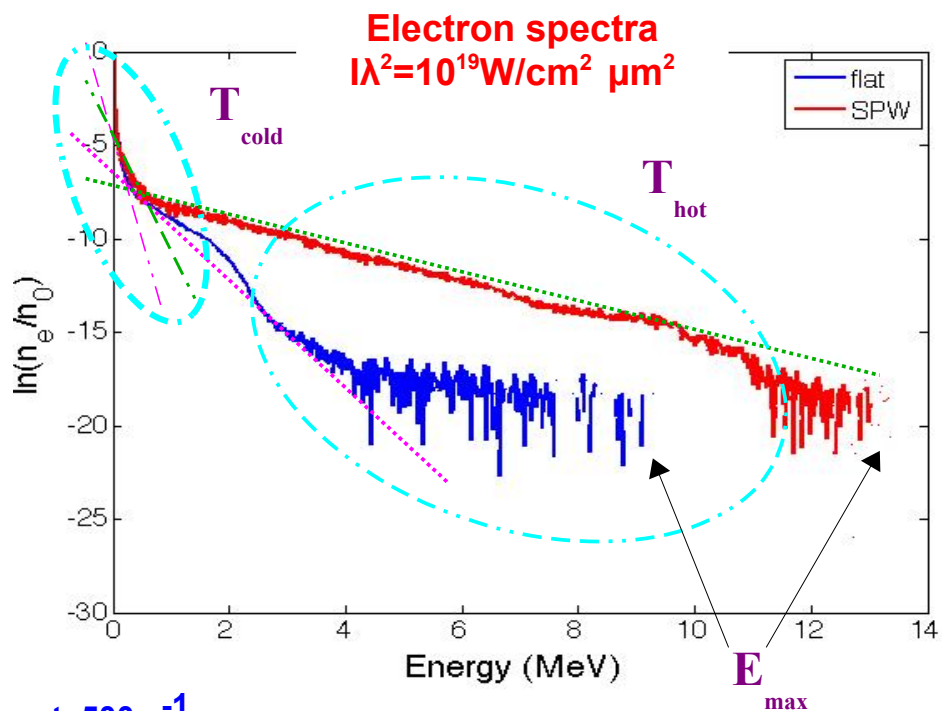
Electron bunches are accelerated into the plasma bulk at each wave cycle :

- Possibility to control the electron direction
- Hot electron acceleration along the target surface (y)



# ELECTRON HEATING

## Increase of the hot electron temperature via SPW

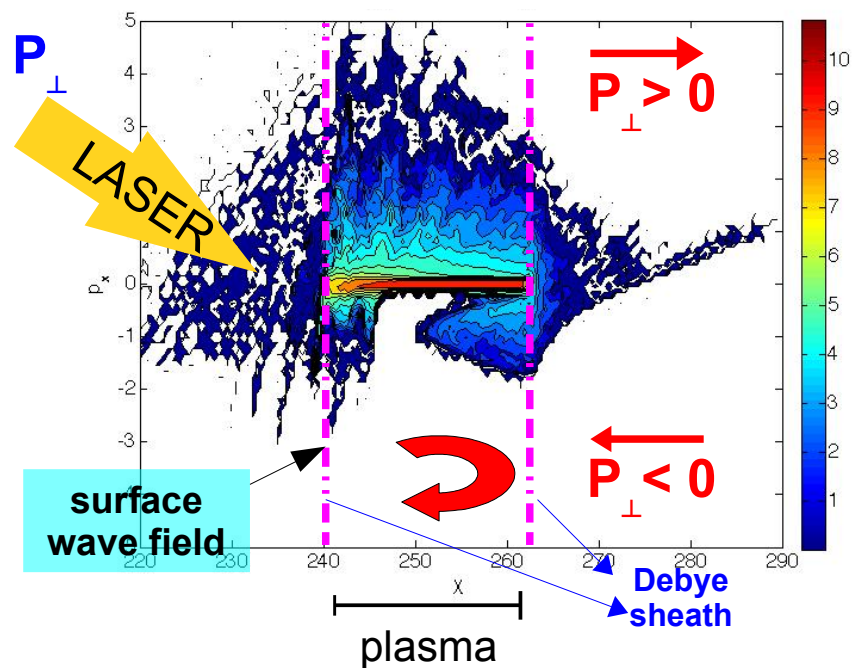


$t = 500\omega^{-1}$   
 ~ some period after the peak laser intensity

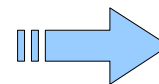
The temperature increases of a factor 2

target	$T_{\text{cold}}$ keV	$T_{\text{hot}}$ keV	$E_{\text{max}}$ keV
SPW	54	1900	13000
flat	38	860	6500

## THIN TARGETS ELECTRON RECIRCULATION



The advantages of SPW are enhanced



**SPW**  
 $h=8\lambda \rightarrow 75\% \text{ abs}$   
 $h=3.5\lambda \rightarrow 85\% \text{ abs}$   
**FLAT**  
 $h=8\lambda \rightarrow 27\% \text{ abs}$   
 $h=3.5\lambda \rightarrow 28\% \text{ abs}$

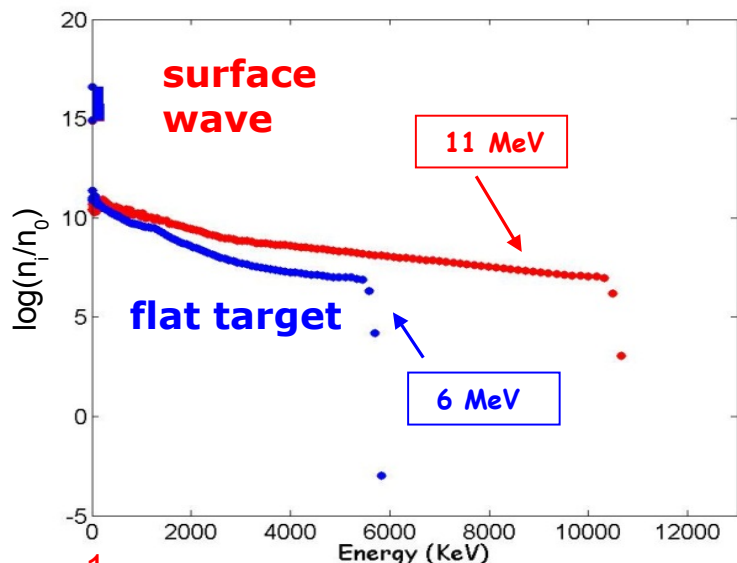


# ION ACCELERATION

## rear side

At the rear surface ions are accelerated by the space-charge field, set-up by hot electrons, in the direction  $\perp$  to the target : Target Normal Sheath Acceleration

Thin target ( $8\lambda$ ): rear surface emission



$t=1000\omega^{-1}$   
after wave extinction

The accelerating field depends on electron temperature and density

$$E_{TNSA} \sim \frac{k_B T_e}{e L_p} \begin{cases} \propto \lambda_D, & t \rightarrow 0 \\ c_s t, & t \gg \frac{\lambda_D}{c_s} \end{cases}$$

$T_e$  increases  $\rightarrow$  **ion emission is enhanced**

Also target the thickness is important as recirculation increases the hot electron density :

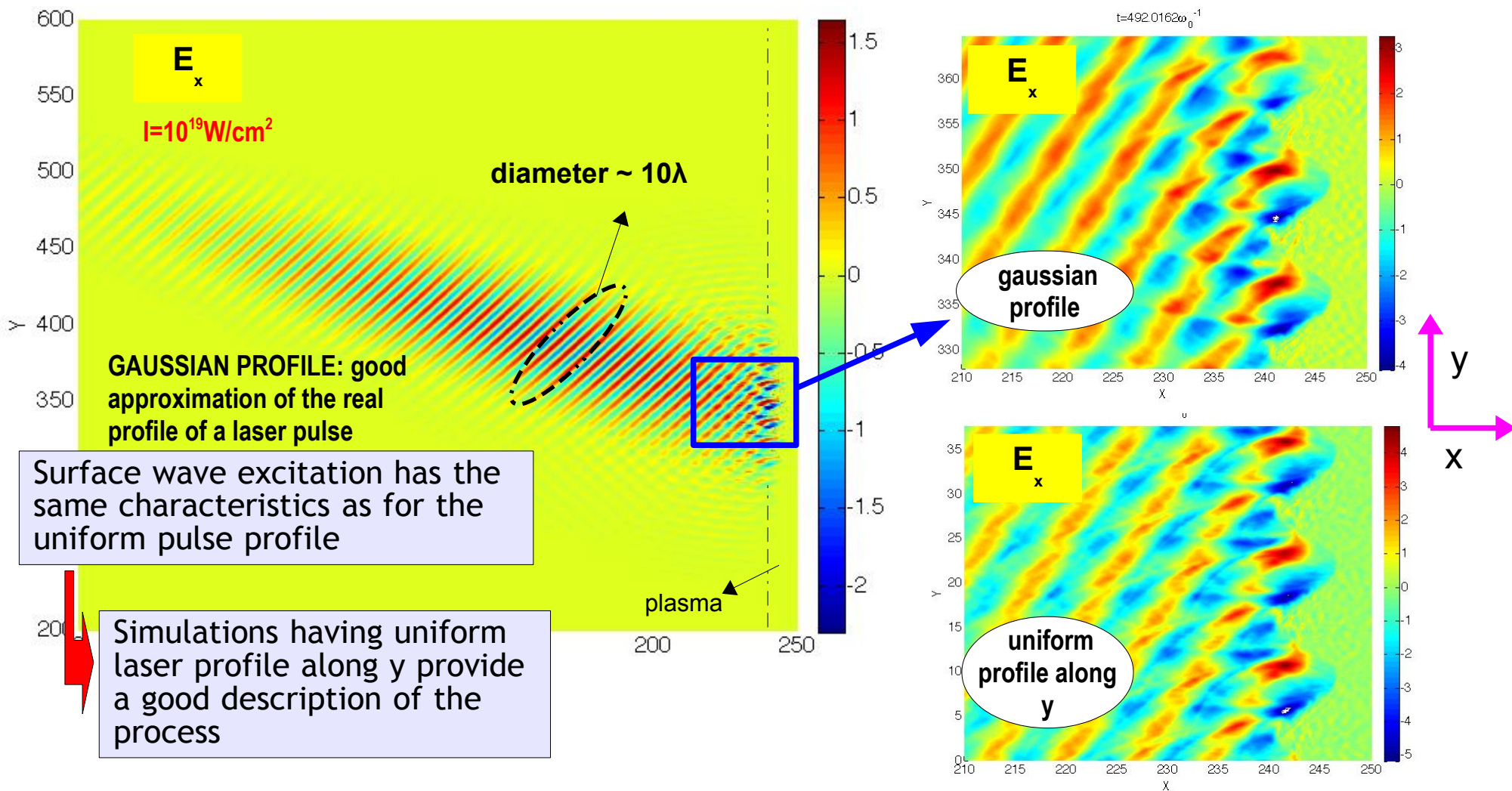
For a laminar target of  $3.5 \lambda$  :  
**8.3 MeV (flat target)  $\rightarrow$  14 MeV (SPW)**  
at  $10^{19} \text{ W/cm}^2$ .

**Ion energy is increased of a factor : 1.7-1.8 compared to a flat target**



# GAUSSIAN LASER PROFILE SPW excitation

Up to now we have considered simulations where the laser pulse profile is **uniform along y**  
We will now analyse the case of a finite transverse profile

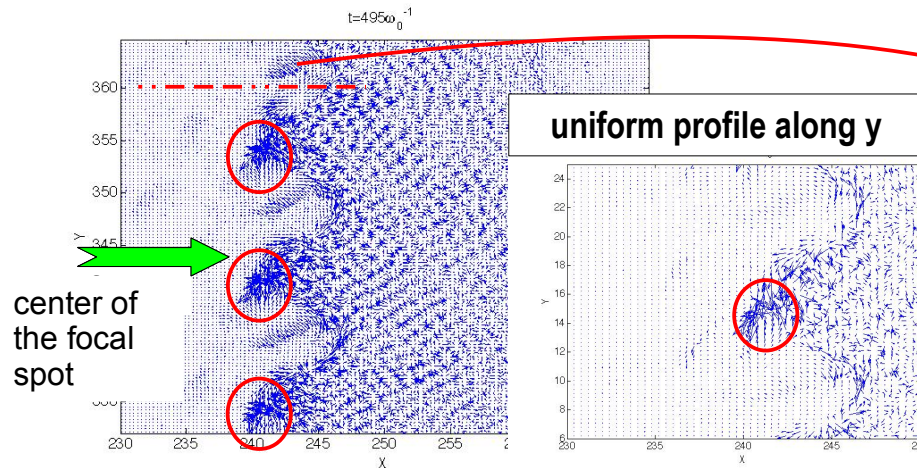
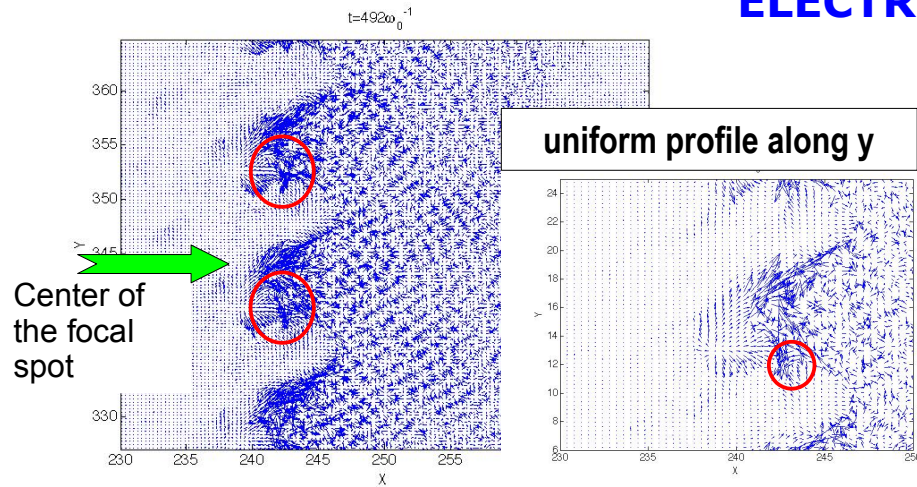




# GAUSSIAN LASER PROFILE electron emission

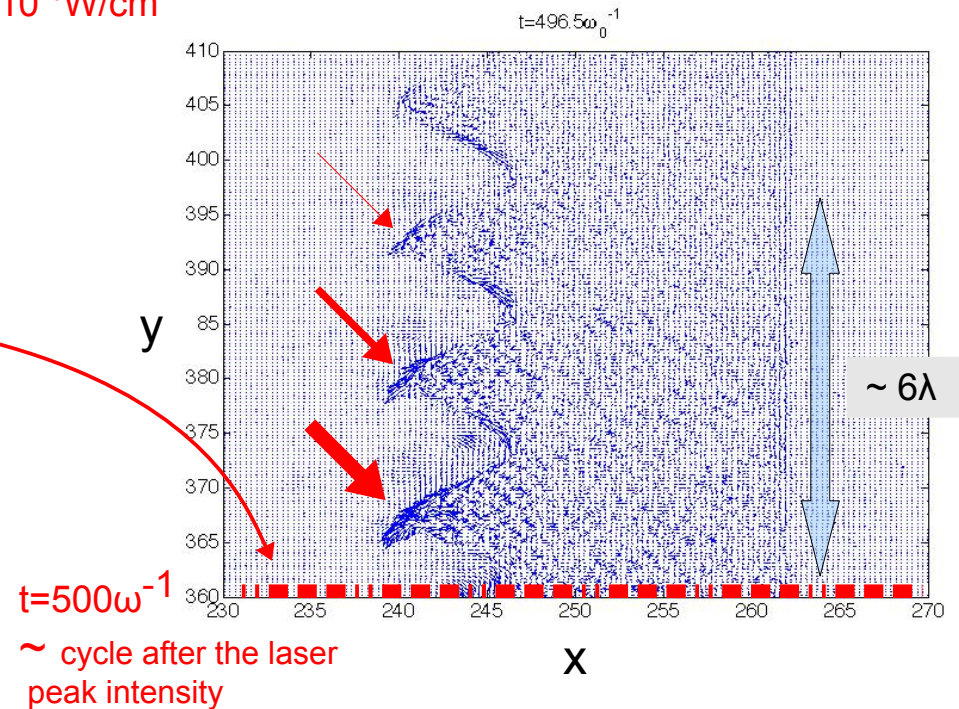
The electron heating and the acceleration of electron bunches have the same characteristics observed for the case of uniform laser intensity along  $y$ :

## ELECTRON CURRENT ( $J = n_e v_e$ )



Far from the laser spot center the electron emission gradually decreases:

$$I = 10^{19} \text{W/cm}^2$$





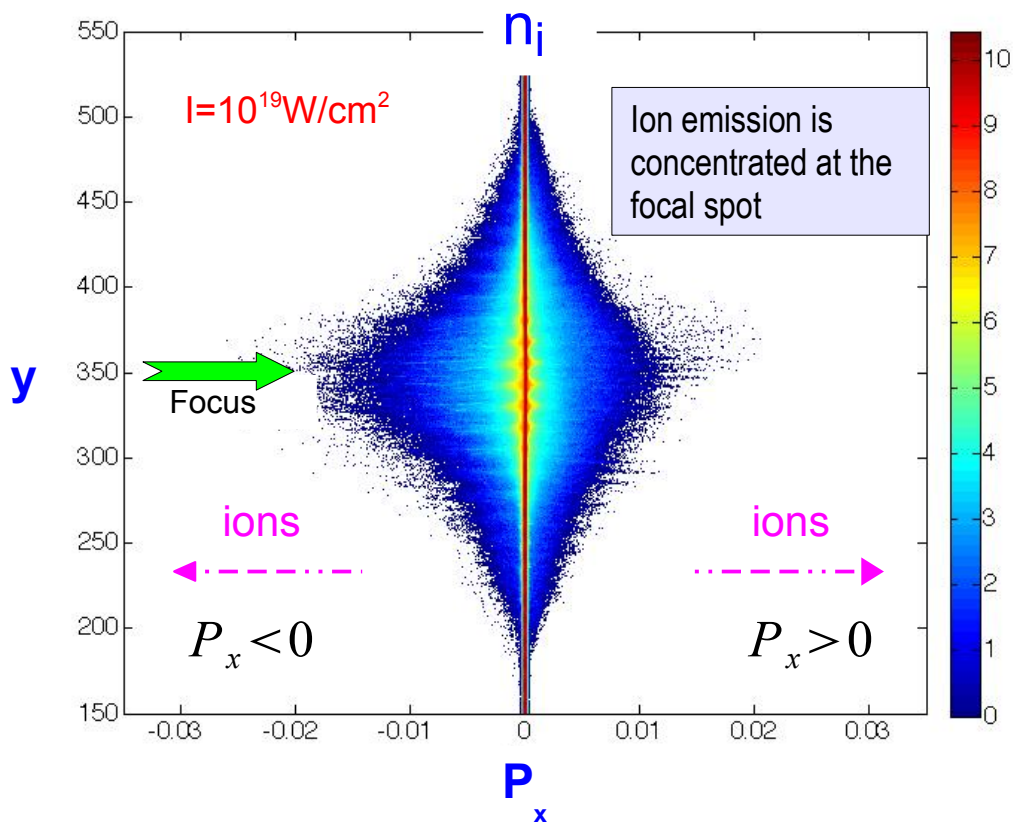
# GAUSSIAN LASER PROFILE ion acceleration

The final energy of the ions accelerated by TNSA decreases for gaussian laser profile compared to the case of uniform laser intensity along  $y$  :  $14 \rightarrow 7.1$  MeV

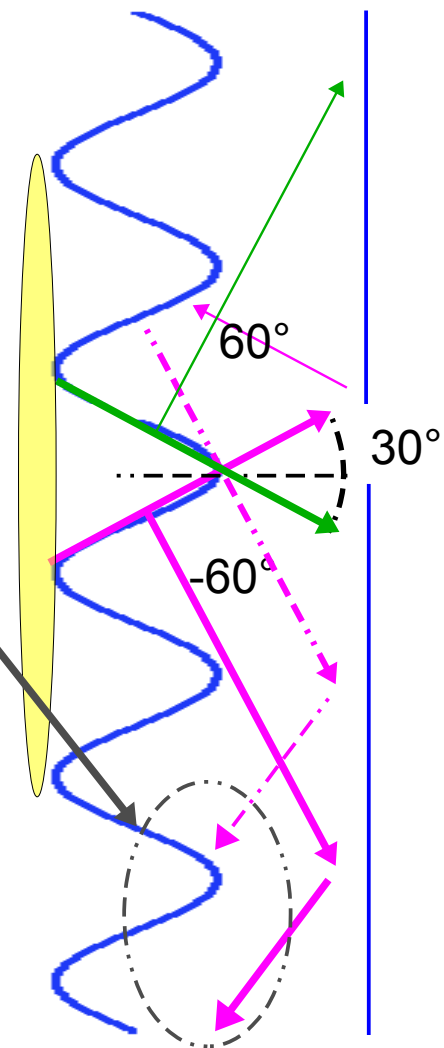
Reduced the efficiency of TNSA : lower ion energy

Reduced production of hot electrons as the intensity decreases far from focal spot

Re-circulation is less efficient due to the angular direction of electrons : the density of hot electrons at a given point decreases



Nevertheless the ion energy is increased by a **factor 1.8** compared to a flat target :  
 $4$  MeV (flat)  $\rightarrow$   $7.1$  MeV (SPW)  
**!The same factor as for uniform laser intensity**







## CONCLUSION

- Enhancement of absorption via resonant surface wave excitation 28%→85% (thinnest target,  $I=10^{19}\text{W/cm}^2$ ).
- Mechanism efficient for high laser intensity  $>10^{18}\text{W/cm}^2$ .
- Generation of high energy electron bunches ( $\sim 14\text{MeV}$  at  $10^{19}\text{W/cm}^2$ ).
- The angular distribution and direction of hot electron can be controlled.
- The energy of the ions emitted via TNSA is increased by a factor  $\sim 2$ , even for a gaussian shape.

Experimental campaign: projet LASERLAB June 2012

PHI-CEA ; CNR-INO, Pise  
CTU, Prague ; LULI-Polytechnique  
LSI-CEA/Polytechnique ; CELIA,  
Bordeaux



- ✓The SPW is excited using an high contrast ( $>10^{11}$ ) pulse : absorption peak.
- ✓The ion energy is increased by a factor  $\sim 2$  : from 2.2 to 5 MeV at  $I=10^{19}\text{W/cm}^2$



# ACKNOWLEDGEMENTS

M. Raynaud, CEA/LSI,CNRS, Ecole Polytechnique



C. Riconda, UPMC, TIPS/LULI,CNRS, Ecole Polytechnique



A. Héron, CPHT, CNRS, Ecole Polytechnique

J.C. Adam, CPHT, CNRS, Ecole Polytechnique

A. Macchi, CNR/INO, Università di Pisa



Equipe PHI-CEA/SPAM

Allocation de temps de calcul GENCI

