Laser-generated ion plasma gratings and applications

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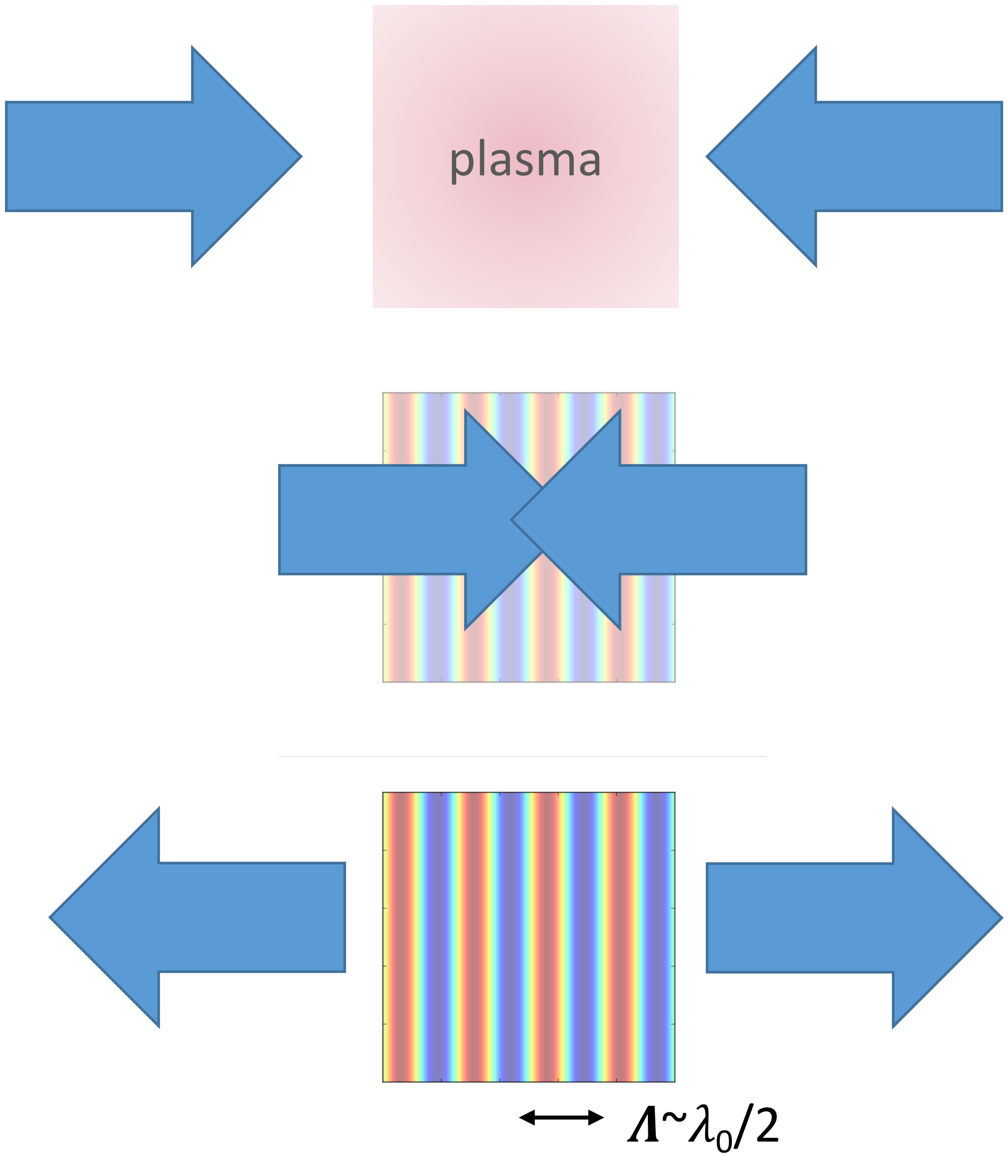
How do we create a quasi-neutral (ion) plasma grating ?



Two identical counterpropagating lasers cross in an underdense plasma such that :

$$I_{14}\lambda_{0p}^2 > 1.1 \times 10^{-1} T_e^{3/2} (n_c/n_0)(1 - n_0/n_c)^{1/2}.$$

Typically

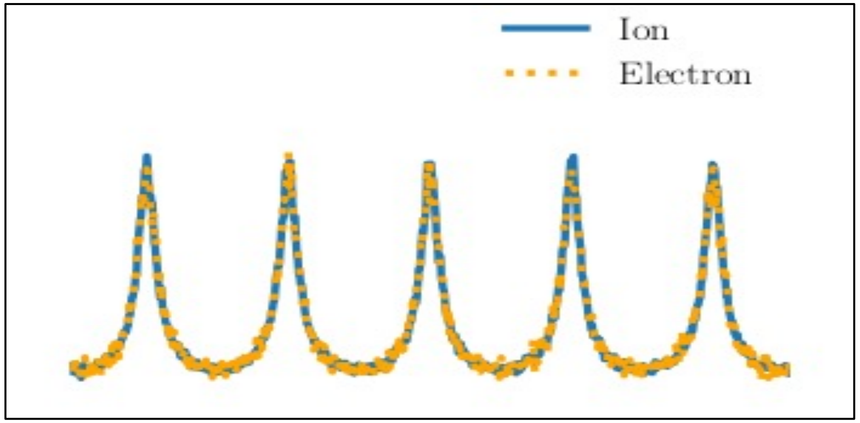
$I\,\lambda_0^2 = 10^{15}\text{-}10^{16}$ Wμm^2/cm^2

$a_0 \propto \sqrt{I\,\lambda_0^2} = 0.025\text{-}0.13$

$\omega_0 \tau_L >> \sqrt{m_i/2Zm_e}\,/a_0$

N.B. crossing can be at an arbitrary angle or at the surface of an overdense plasma

Why a quasi-neutral plasma grating?



- Can sustain laser intensities 5 order of magnitude higher than damage threshold of solid-state optical elements

- Has finite lifetime (transient), but long enough to allow light manipulation

- Can be tailored to desired caracteristics for applications

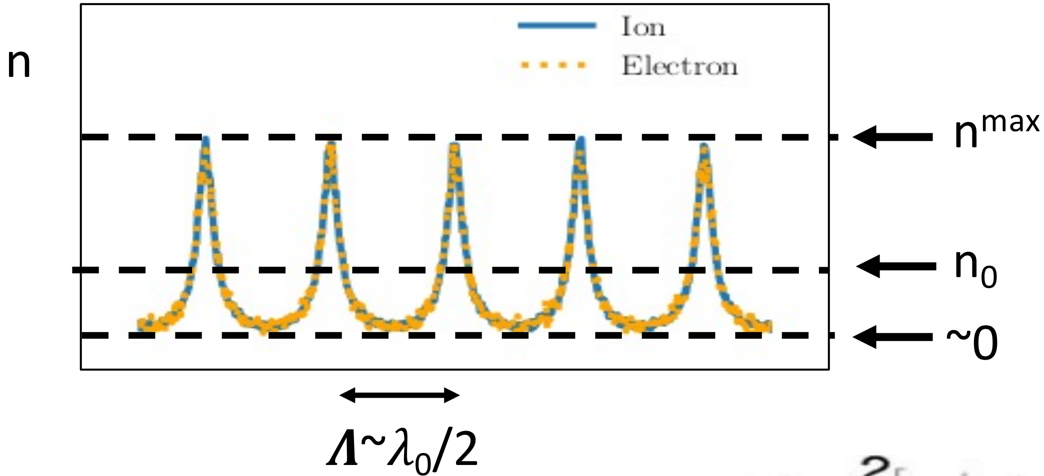
- In a ‚pump-seed' configuration can induce energy transfer and pulse amplification (e.g. sc-SBS amplification)

  JR Marquès et al. Physical Review X 9, 021008 (2019)

Many applications in the literature as "transient plasma photonic crystals"
polarizer, waveplate, hologram, surface grating, etc. *

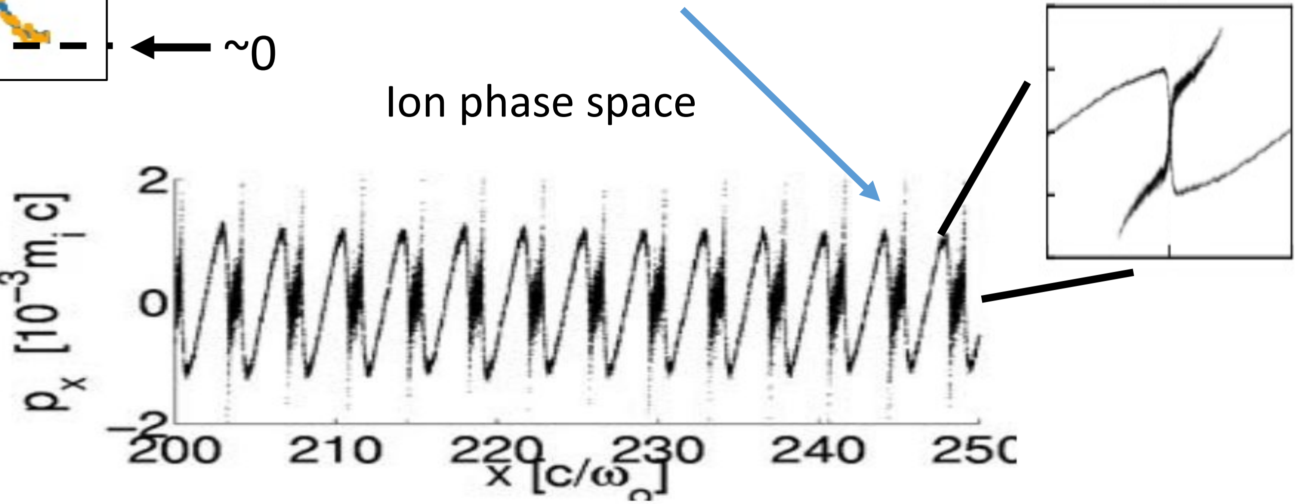
**G. Lehmann and K. H. Spatschek, PRL 2016, PRE 2018, PRE 2019*
S. Monchocé et al., PRL 2014, A. Leblanc et al., Nat. Phys. 2017
Peng et al. MRE 2019, Peng et al. PRApl 2021
P. Michel PRL 2014, PRX 2020, Goyon at al. PRL 2021

Peak density in a Transient Plasma Photonic Cristal (TPPC)

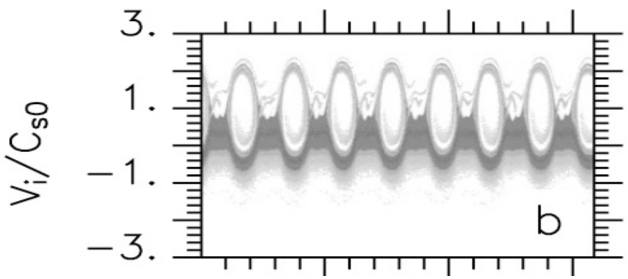


We can choose n0 and λ_0, but n_{max}?

The grating peak density n_{max}/n_0 is limited by kinetic effects : X-type wavebreaking



As opposed to O-type wavebreaking in standard IAW (and EPW)



X-type wavebraking was observed in PIC simulations* :
fluid theory allows to calculate the peak density that can be obtained

*D. W. Forslund et al., *Phys. Fluids* 1975

Fluid equations for electrons and ions, quasi-neutral grating (ν >> 1),
force= ponderomotive potential (crossing lasers) and electron pressure term

$\varphi = \varphi_p + \varphi_{th}$ with $\phi_p = \frac{1}{2}\frac{m_e c^2}{e} a_0^2 \cos(2kx)$ and $\boxed{\phi_{\text{th}} = \frac{3}{2}\frac{T_{e0}}{e}\left(\frac{n_e}{n_0}\right)^2}$

$$\boxed{\mu}\frac{\partial^2 n_e^2}{\partial x^2} - \cos x = \nu\cancel{(n_e - n_i)},$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial (n_i v_i)}{\partial x} = 0,$$

$$\frac{\partial v_i}{\partial t} + v_i\frac{\partial v_i}{\partial x} = \sin x - \boxed{\mu}\frac{\partial n_e^2}{\partial x}.$$

electrons are NOT isothermal !

$x_{unit} = \lambda_0/2$

$t_{unit} = \sqrt{m_i/2Zm_e}\,/(\omega_0 a_0)$

$n_{unit} = n_0$

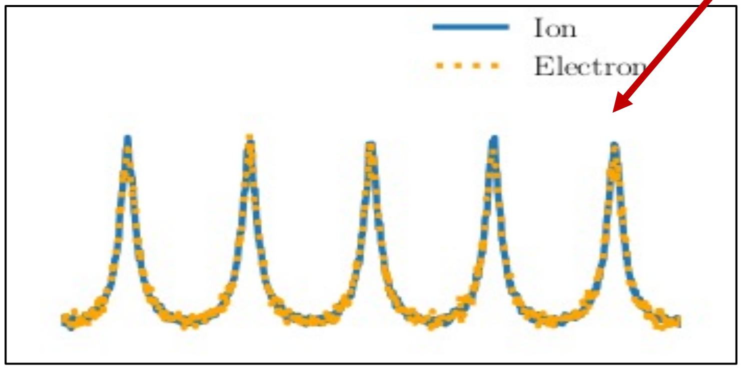
$$\boxed{\mu = 3T_{e0}/(m_e a_0^2 c^2) \propto T_{e0}/I\lambda^2}$$

➔ µ completely describes dynamics of grating

As in O-type wavebreaking, in X-type wavebreaking
the fluid equations allow to calculate the <u>maximum density</u> that can be obtained ,
but not what happens afterwards (i.e. lifetime of grating, kinetic evolution).

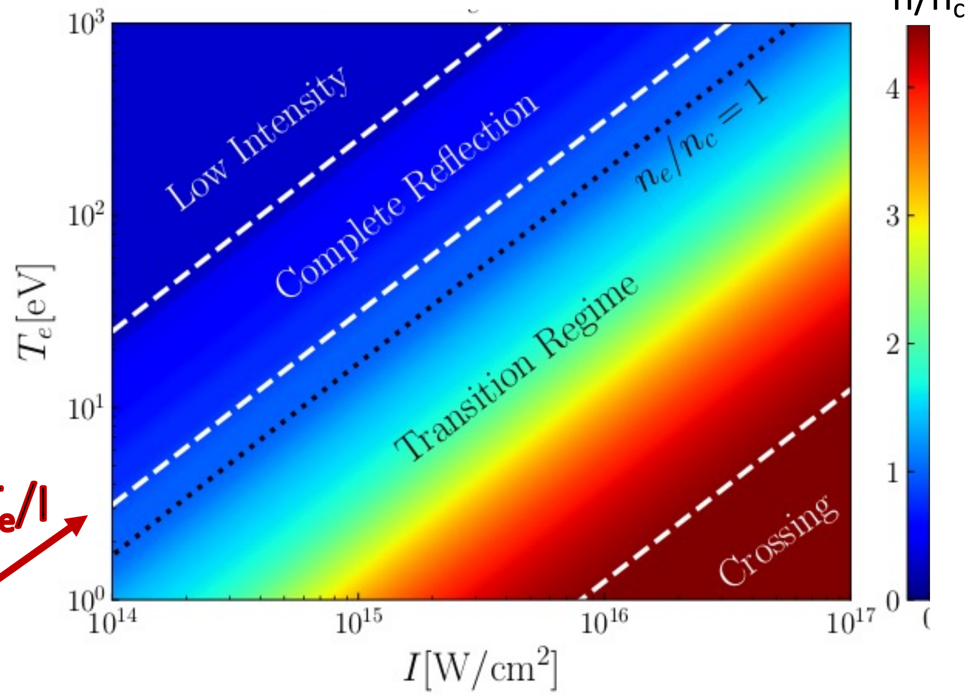
Tailor TPPC to experimental application !

Peak density n^{max}/n_0 depends on μ and can be calculated (numerically) from the fluid equations



n^{max}/n_c (fluid theory)

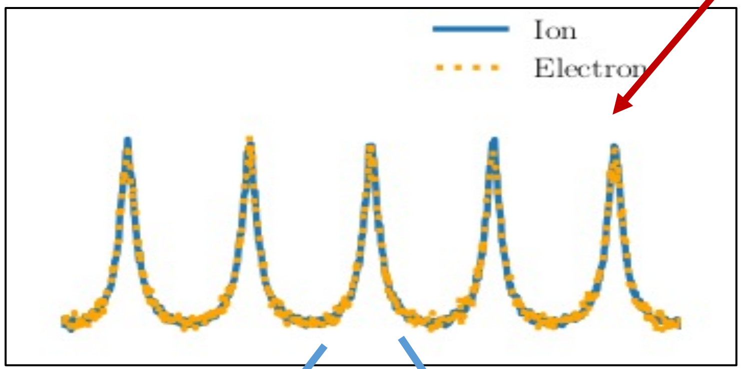
μ ~T_e/I

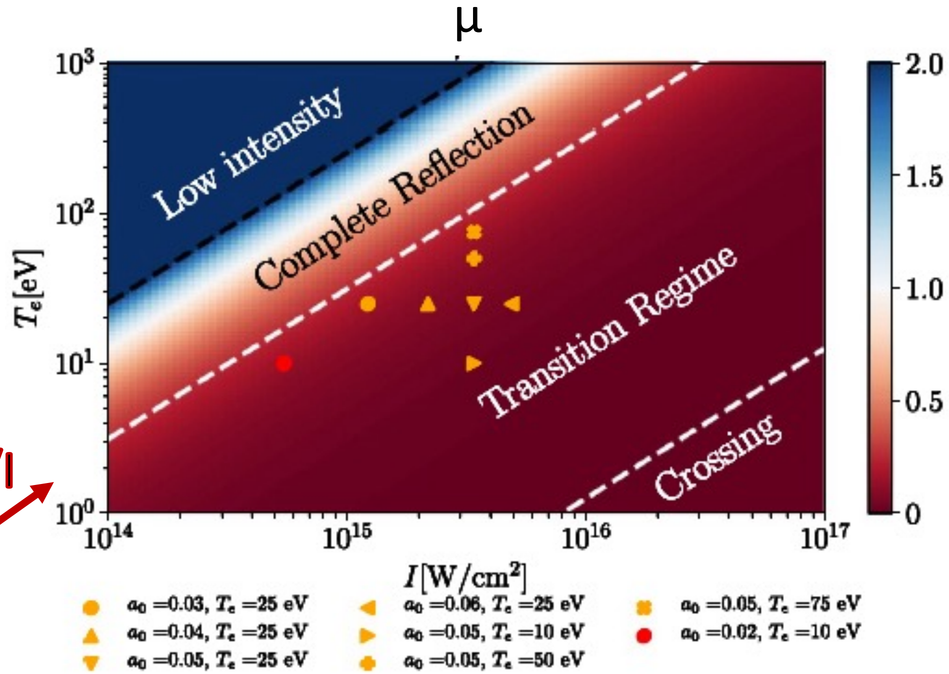


Peng et al. PRE 2019, Peng et al. PPCF 2020

Confirmation by PIC simulations and regimes of ion dynamics

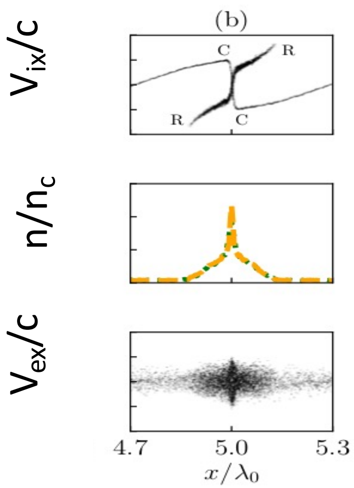
Fluid results for the peak density n^{max}/n_0 agree with values obtained by PIC simulations





$\mu \sim T_e/I$

PIC



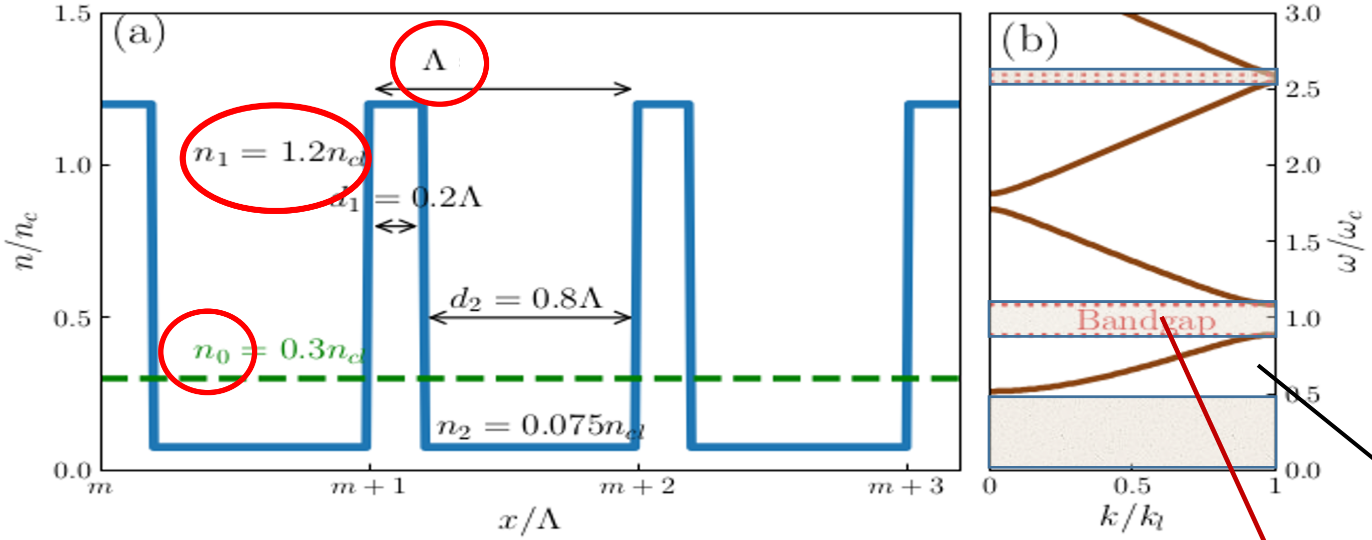
ion kinetic response governs the lifetime of the grating for $\omega_0 t \gg \sqrt{m_i/2Zm_e}\,/a_0$

3 regimes : reflection, transition, crossing

Peng et al. PRE 2019, Peng et al. PPCF 2020

G. Lehmann and K. H. Spatschek, PRL 2016, PRE 2018, PRE 2019

Presence of bandgaps that depend on the grating caracteristics



$k_l=\pi/\Lambda$
$n_{cl}= n_c(2c/\Lambda)$
$\omega_c=ck_l(1+n_0/n_{cl})$ ~ ω_0
n_0 = average density

Light can travel

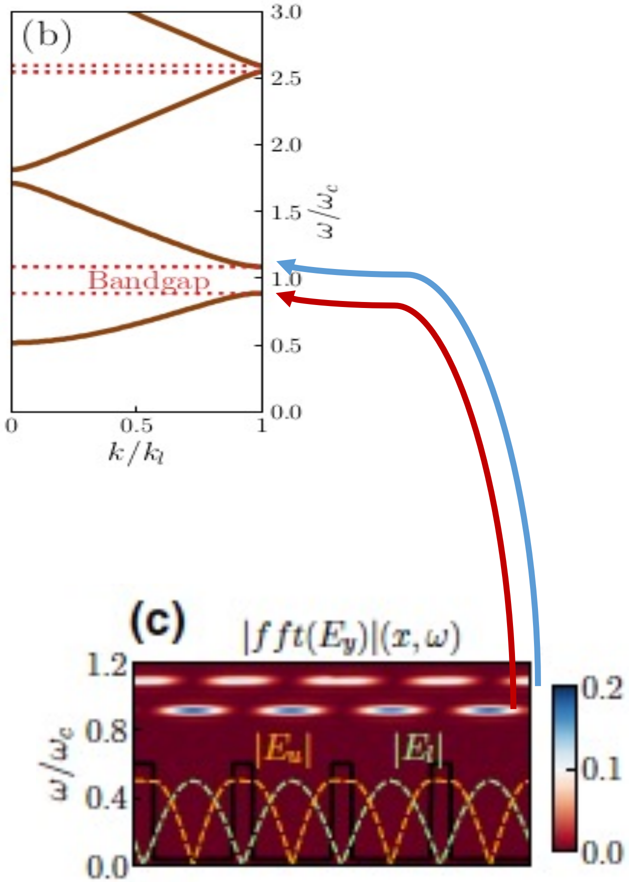
Light cannot travel

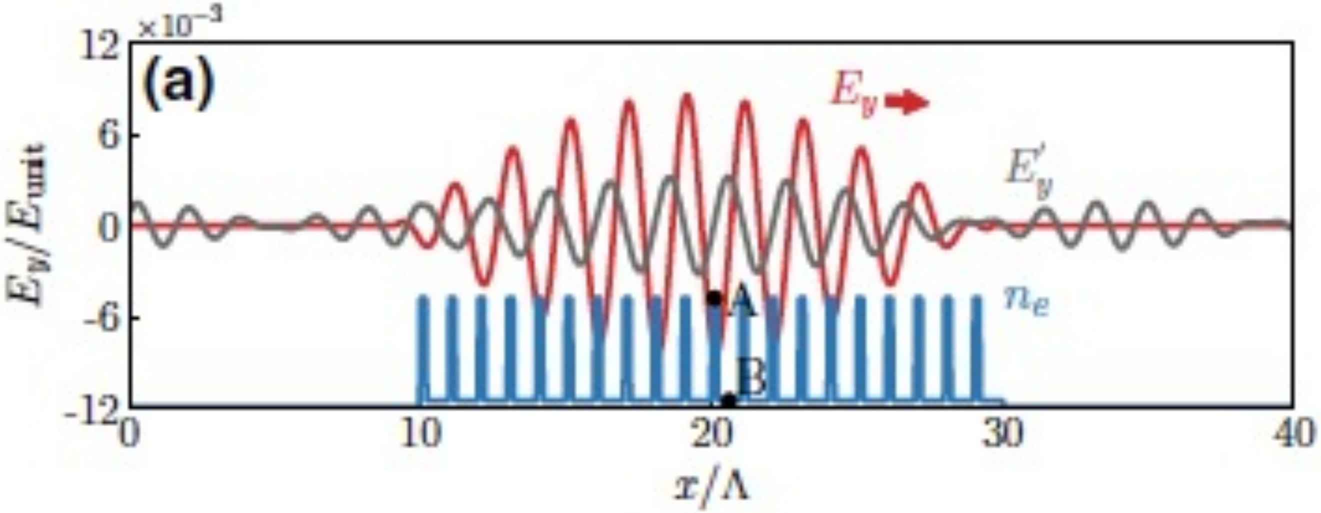
Simple approximate formula for the width of the first bandgap around central frequency ω_c~ ω_0 :

$$\delta\omega \approx \frac{|\eta_1|\omega_c}{1+n_{cl}/n_0}.$$

New application: transient gratings + bandgap allow to modify the laser frequency

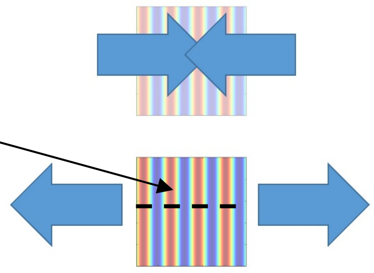
A light pulse is propagating in a
<u>suddenly created grating</u>* with $\Lambda=\lambda_0/2$:
pulse wavelenght preserved, but
frequency splitting and trapping + leaking of light.

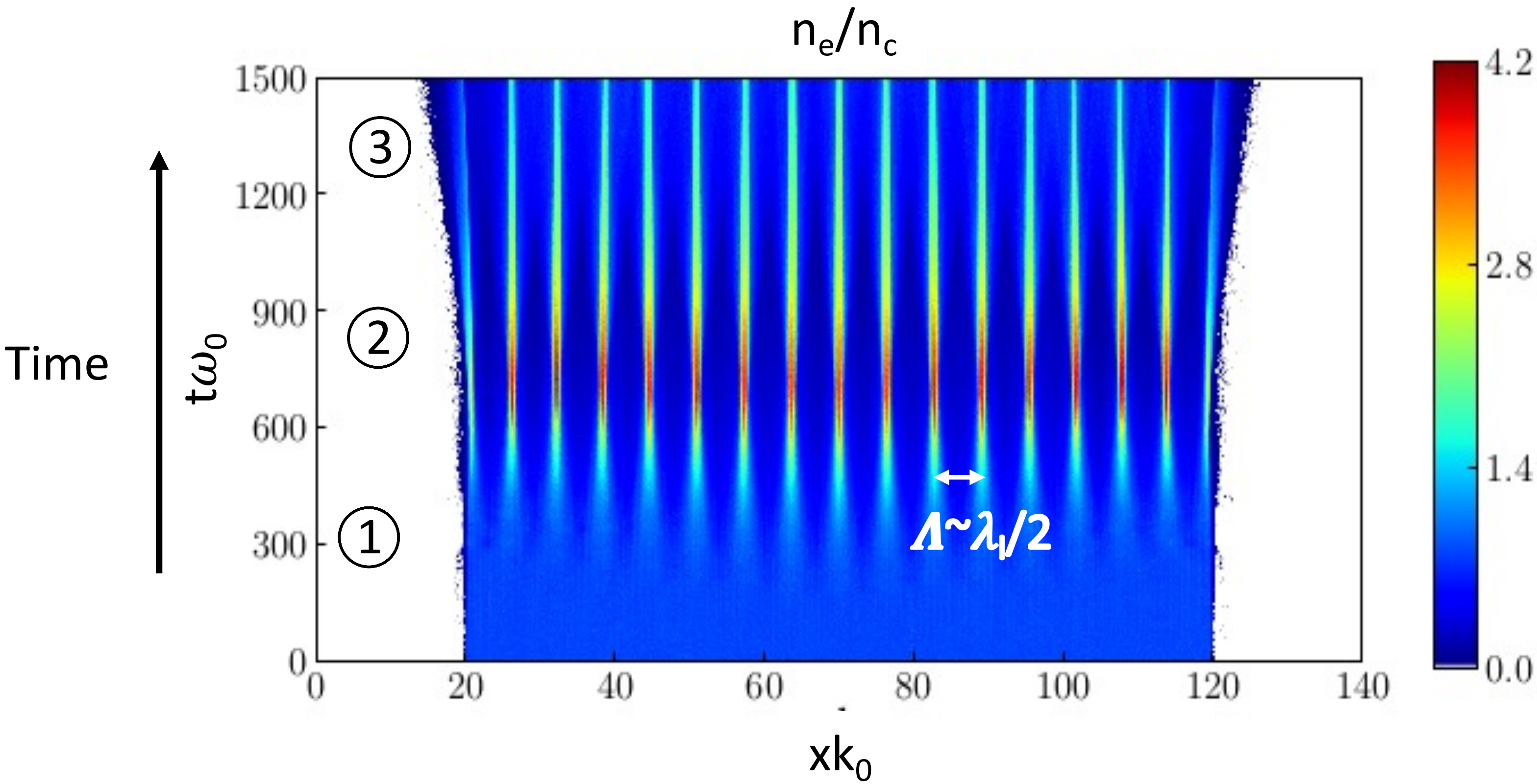




*can be created in gas, induced by ionization
Zhang et al. Plasma Phys. Control. Fusion 63 (2021) 095011

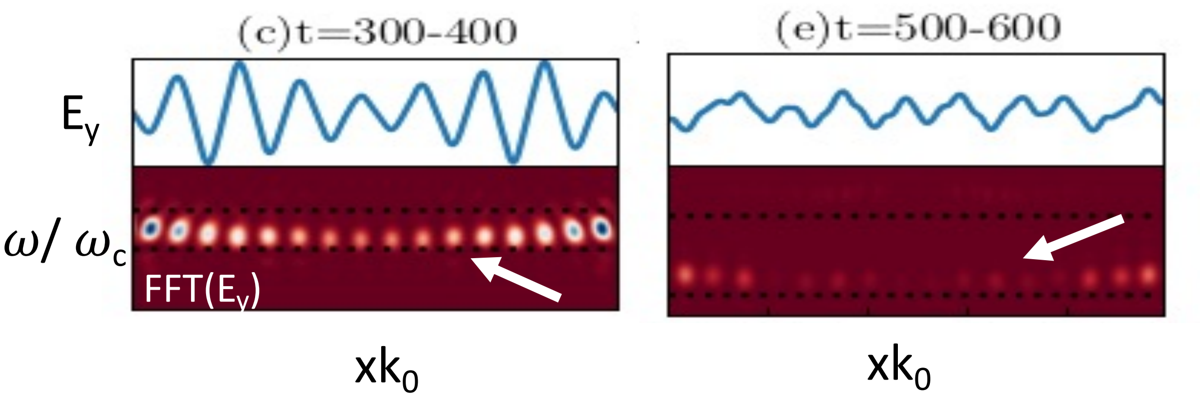
The grating is now generated in a plasma by two crossing laser pulses : <u>time dependent</u> plasma grating (1D lineout) from PIC simulations Smilei)



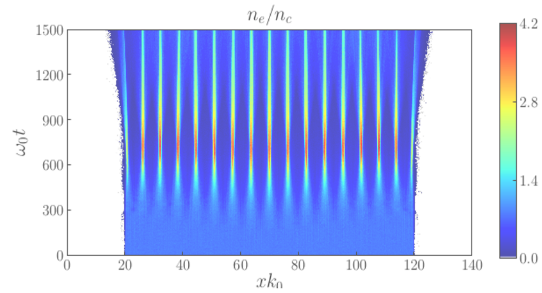


1. The density peaks and <u>bandgap</u> increase up to maximum value
2. Finite lifetime
3. Depending on regime, cycle repeats

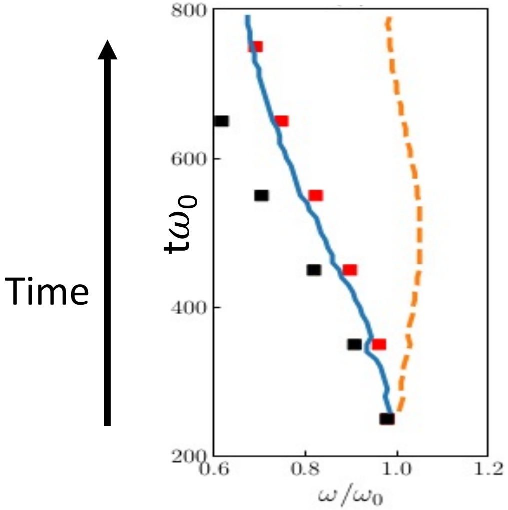
Spatial scale is unchanged but the grating evolves with time -> modification of laser frequency



Laser generated grating



Bandgap



- laser frequency (PIC)
- analytical model

$$\delta\omega \approx \frac{|\eta_1|\omega_c}{1 + n_{cl}/n_0}.$$

---- downshift (semi-analytical)

---- upshift (semi-analytical)

➔ During the grating formation, the pumps laser frequency adjust to the edges of the forbidden zone

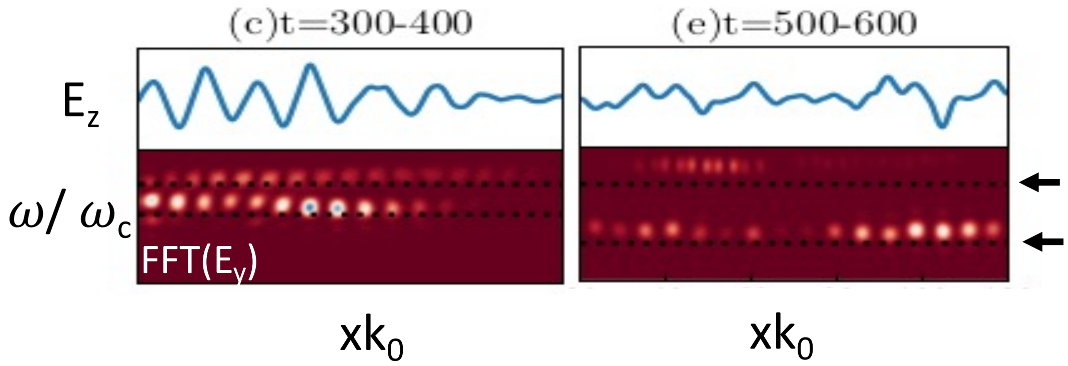
➔ The beating of the crossing lasers generates a pattern which is consistent with only ONE of the 2 possible eigenmode solutions

➔ Corresponds to the low edge of the bandgap, DOWNSHIFT

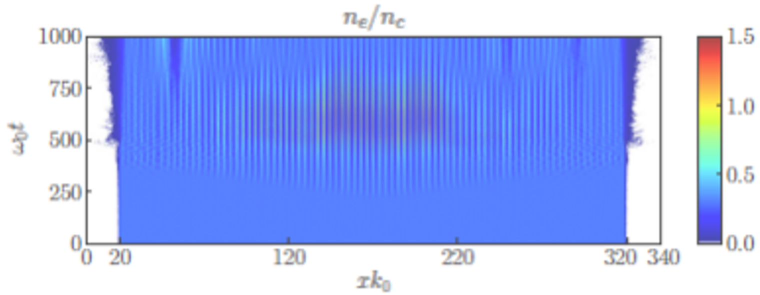
➔ Light is either trapped or leaks out of the grating

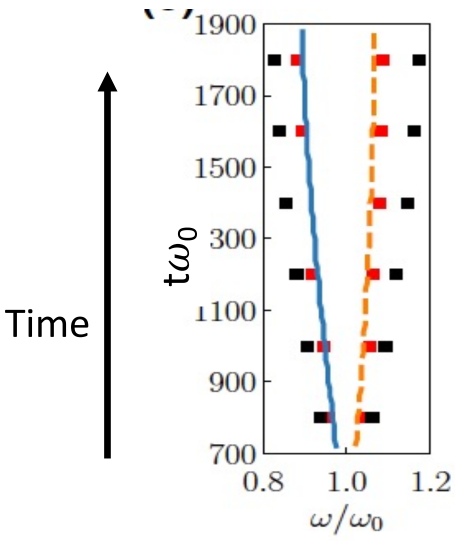
Test pulse on TPPC : frequency split

Test pulse with polarization ⊥ to the polarization of the pulses generating the TPPC



Laser generated grating





- laser frequency (PIC)
- analytical model

$$\delta\omega \approx \frac{|\eta_1|\omega_c}{1 + n_{cl}/n_0}.$$

---- downshift (semi-analytical)

---- upshift (semi-analytical)

➔A free-travelling laser convert its frequency to BOTH the upper and lower edge of the bandgap (polarization ⊥ to pumps in order to avoid coupling)

➔Need to synchronize the test pulse with the pumps to ‘see‘ the growth of the grating

➔Light is either trapped or leaks out of the grating

Peng et al. PRApl 2021

The parameter $\mu \propto T_{e0}/\mathrm{I}\lambda^2$ governs the Transient Plasma Photonic Crystal evolution

- Fluid theory allows to calculate n_{max}
- 3 different regimes of kinetic theory

TPPC evolution induces :

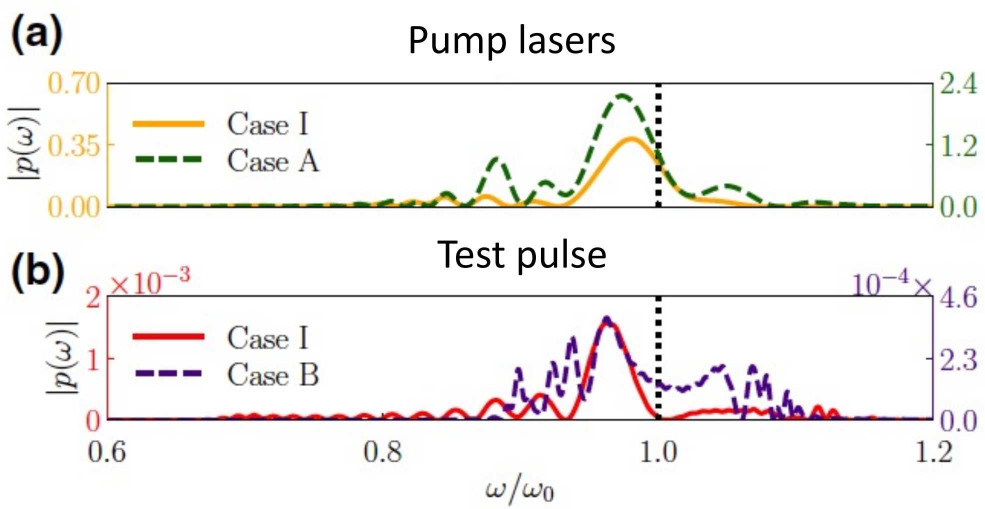
- Downshift of the pump lasers
- Frequency splitting of a test pulse
- Partial wave trapping

Possible applications :

- Downshift: seed pulse for Raman amplification
- Generate dual color X-ray by Thomson/Compton scattering(TCS) of frequency splitted laser pulse $\omega_{xray} \approx 4\gamma^2\omega_{o\pm}$

Thank you for your attention

Time integrated spectrum of outgoing light for different gratings

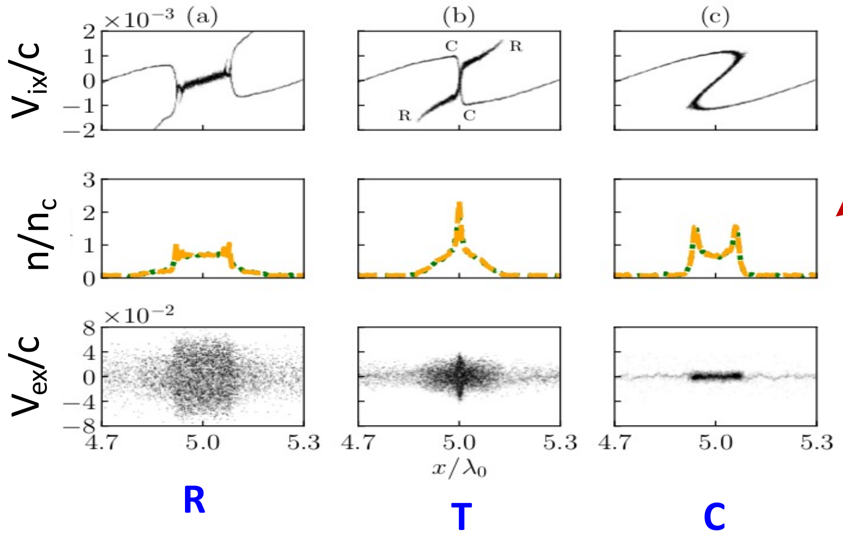


➔ control everything via I_o, T_e, n_o with the parameters:

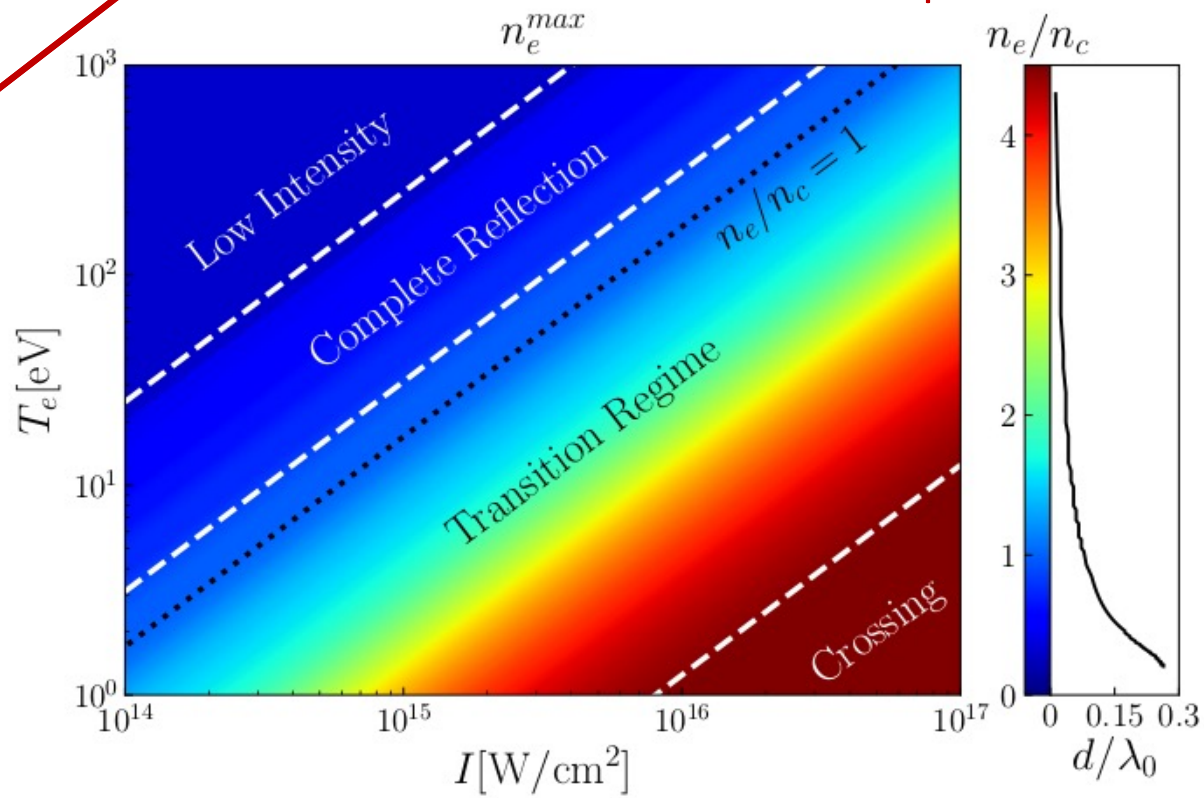
$$\boxed{\mu = 3T_{e0}/(m_e v_0^2)} \quad \& \quad \boxed{t_{unit} = \sqrt{\frac{m_i}{2Zm_e}}\frac{1}{k_l v_0}}$$

→ ion kinetic response governs dynamics of the grating (μ identifies 3 regimes) $t_{\text{unit}} = \sqrt{\frac{1}{2}\frac{Zm_e}{m_i}}(kv_0)^{-1}$

- Reflection (R): μ >>1 large electron pressure → ion reflection & grating stops growing
- Transition (T): μ >1 → large compression but still X-type wave breaking
- Crossing (C)): φ_{th} too small, ions oscillate in potential well → density reaches largest values



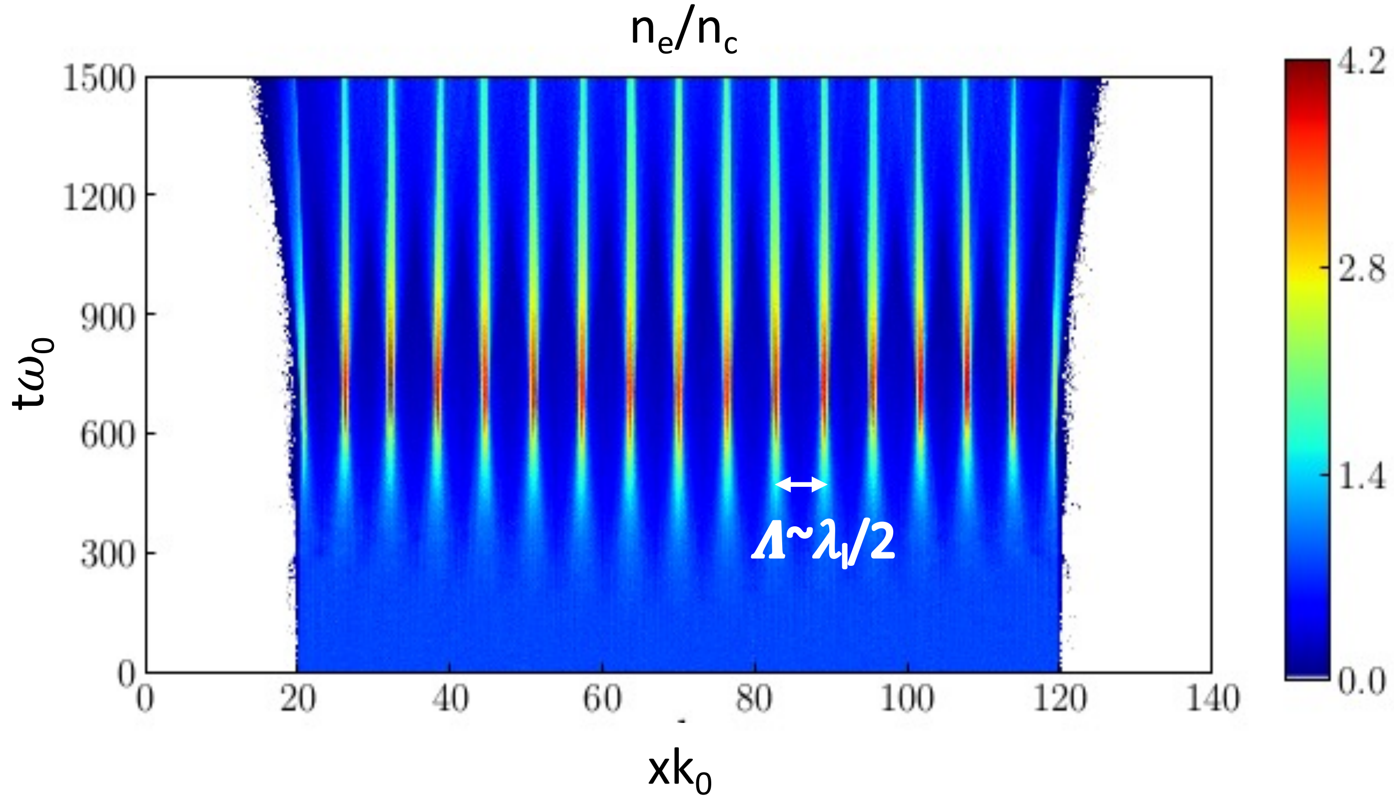
Peak density and grating size can be calculated from the fluid equations

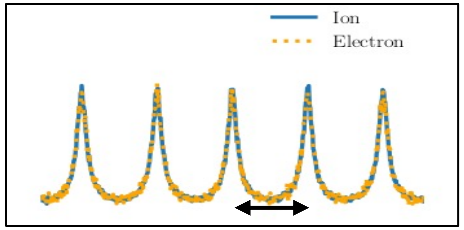


→ tailor grating to experimental application !

The grating is now generated by two crossing laser pulse (top view)

Time





Λ~$\lambda_0/2$

Typical scales and grating caracteristic
the density peaks (and thus the band gap) increase with time,
spatial scale unchanged, frequency changes.
Lifetime, decrese.