Electron sources from plasma

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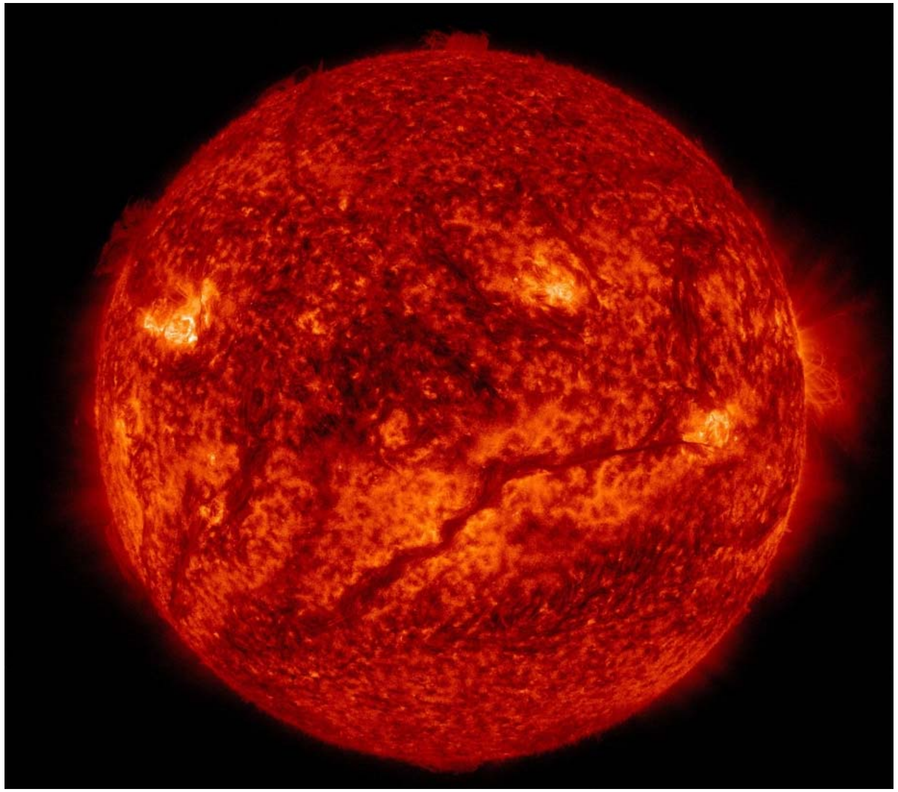
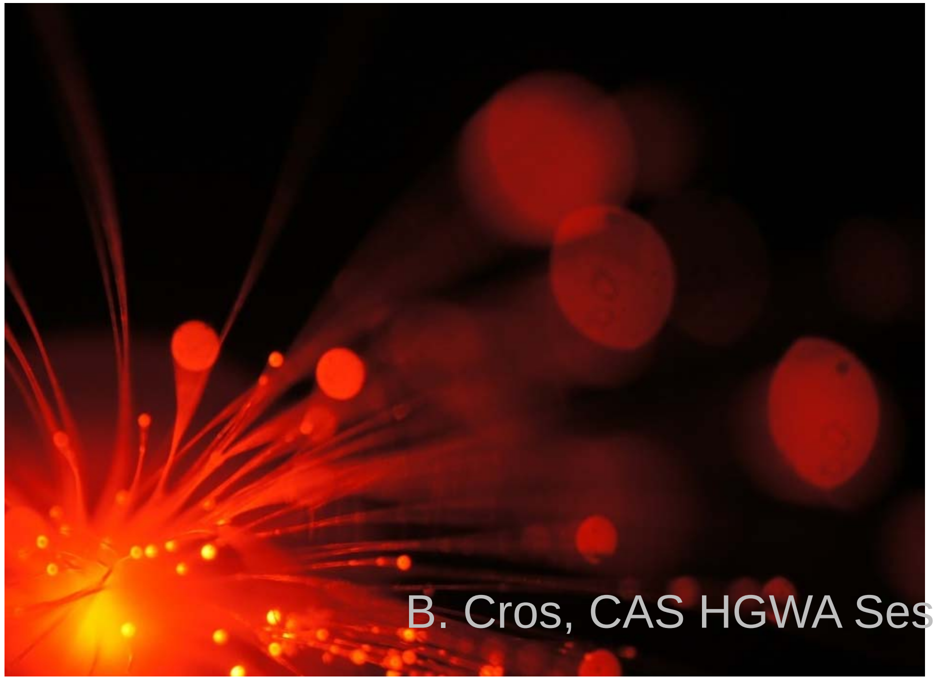
Plasmas are sources of accelerated particles and radiation



- A plasma is a reservoir of free electrons moving relatively to ions and eventually recombining with them
- Under specific conditions they emit bursts of fast particles and radiation: solar wind, and northern light

- Laser interaction with plasmas can create extremely non linear situations and expel electrons out of the plasma
- Can we control this mechanism and use it to generate injectors for accelerators?



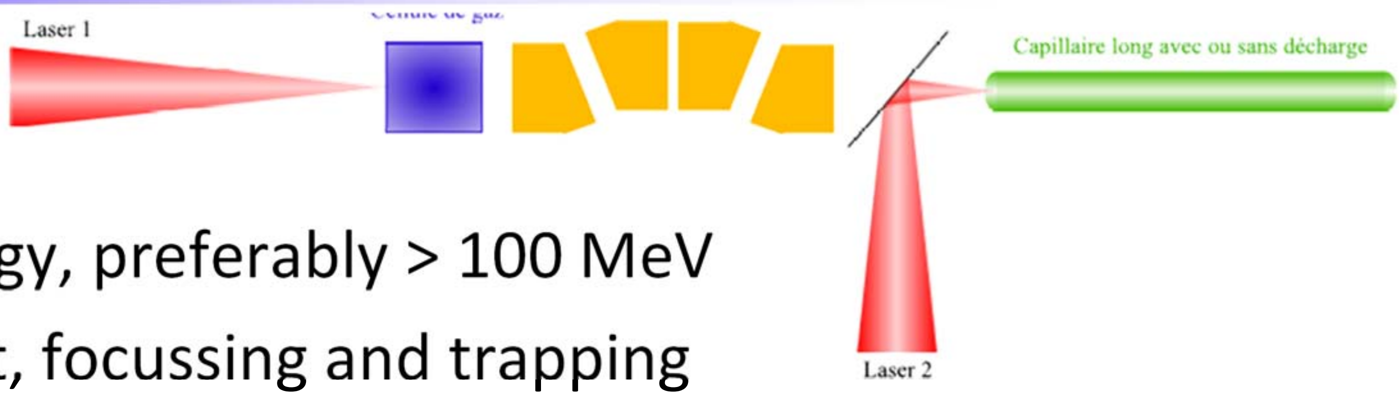
Outline

1. Properties of electron sources needed for applications
2. Mechanisms of electron trapping and acceleration in a plasma wave
3. Electron Sources created in non Linear regimes
    1. Self-injection
    2. Additional laser beam
    3. Acting on the plasma
    4. Combined methods
4. Towards external multi-stage acceleration

Requirements for electron sources depend on the specificities of applications

- Applications often require transport and focussing of the beam, together with stable and reproduceable parameters from shot to shot
- One important case is an injector for multistage plasma accelerator (benefits from the short pulse duration)

Electron injection into a 2nd plasma: guidelines for optimum acceleration



- Relativistic energy, preferably > 100 MeV
  - For transport, focussing and trapping
  - Small energy spread
- Small emittance/divergence and short duration (fs)
  - Focussing to micron size
  - To preserve beam quality and avoid particle loss during acceleration
- Stability of pointing and reproducibility of parameters
- Synchronisation with 2nd stage driver (laser or particle) beam

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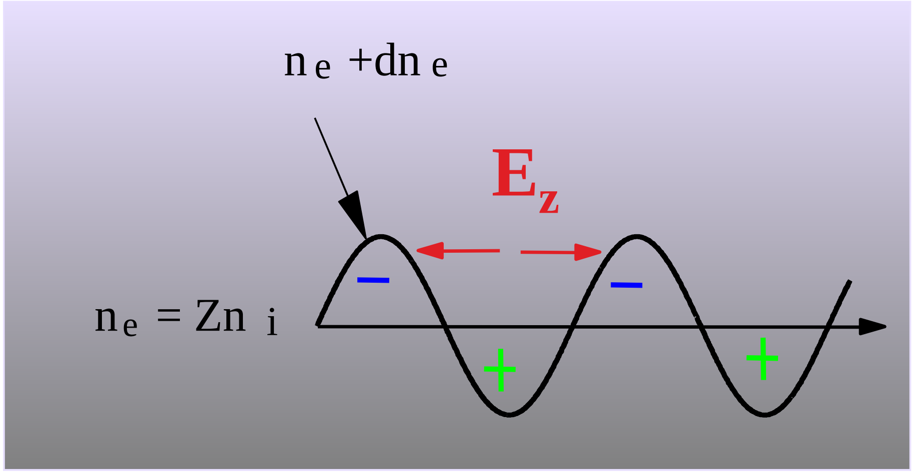
- The requirements on the electron source are related to the properties of the plasma wave - or plasma cavity or accelerating structure

>>> reminder

Large longitudinal electric field associated to a plasma wave

Accelerating fields > 10 GV/m for LWFA



- Space charge field and plasma wave

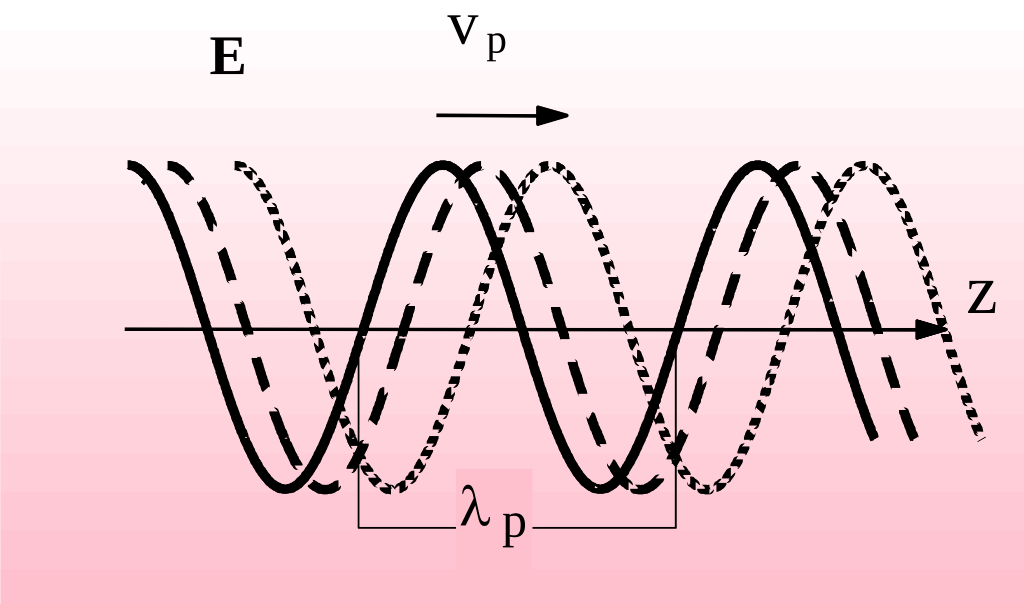
  wavelength

  $\lambda_p[\mu m] \sim 33\ (n_e[10^{18} cm^{-3}])^{-1/2}$

$$E_z\ [GV/m] \sim 96\ (n_e\ [10^{18}\ cm^{-3}])^{1/2}\ dn_e/n_e$$

$$E_z\ [GV/m] = 1.35\ 10^{-18}\ I_{max}[Wcm^{-2}](\lambda[\mu m])^2/\tau[ps]$$

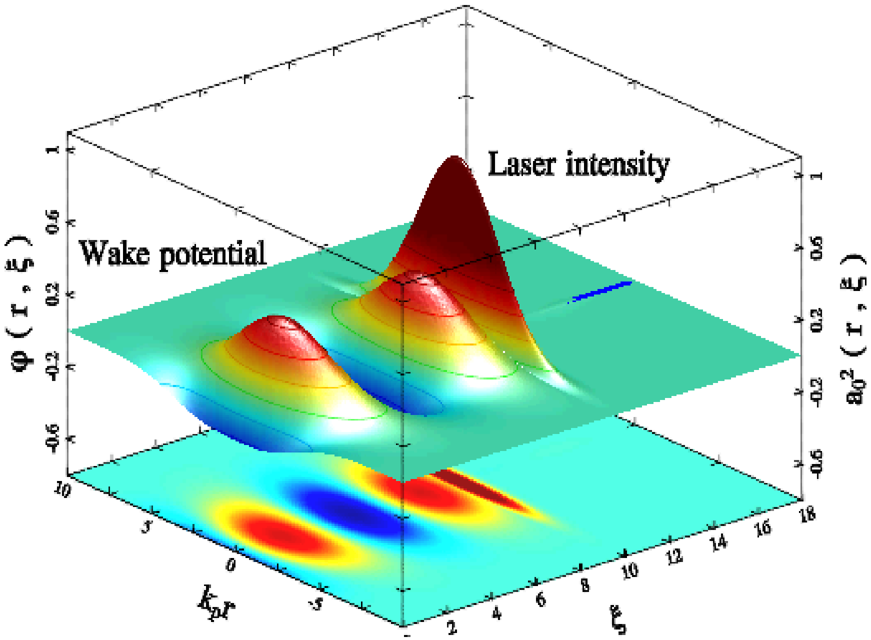
Relativistic plasma wave



- Laser driven plasma wave has a **phase velocity** $\mathbf{v_p}$ of the order of the **laser group velocity** $\mathbf{v_g}$

$$v_{\rm g} = \frac{\partial\omega}{\partial k} = c\sqrt{1 - \frac{\omega_{\rm p}^2}{\omega^2}},$$

Driving laser amplitude chracterized by a normalized parameter



- Laser strength parameter

  a ~ eA/mc²

normalized laser vector potential

- Peak value

  $a_0 \sim 8.5\times10^{-10}\ \lambda_0[\mu m]\ I_0^{1/2}[Wcm^{-2}]$

- Quasilinear regime or weakly relativistic regime

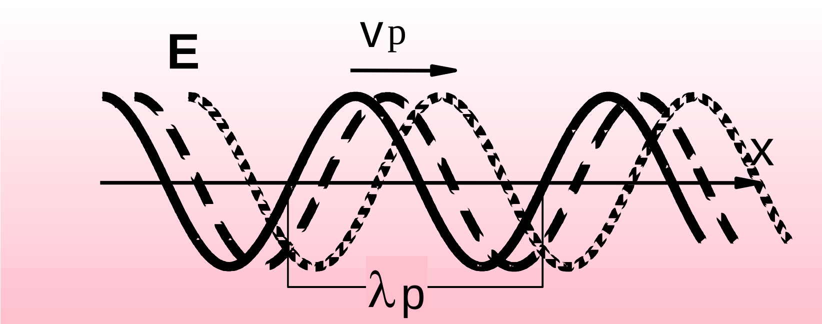
  $a_0 \sim 1$

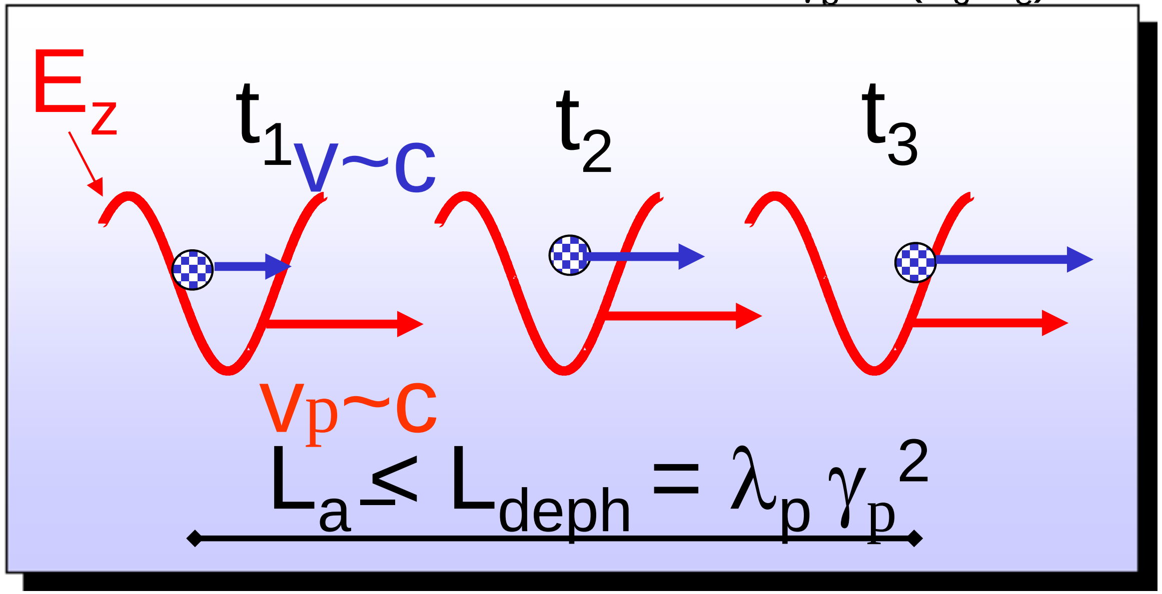
Trapped electrons are accelerated in a plasma wave

Relativistic electrons are trapped and accelerated over the dephasing length

$\gamma_p \sim (n_c/n_e)^{1/2}$

- Relativistic plasma wave:
  Too slow or too fast electrons do not stay long with the wave





Energy gain over dephasing length

- Energy gain

$\Delta W = e\, E_z\, L_a \quad \sim 4mc^2\gamma_p{}^2$

- Relativistic factor

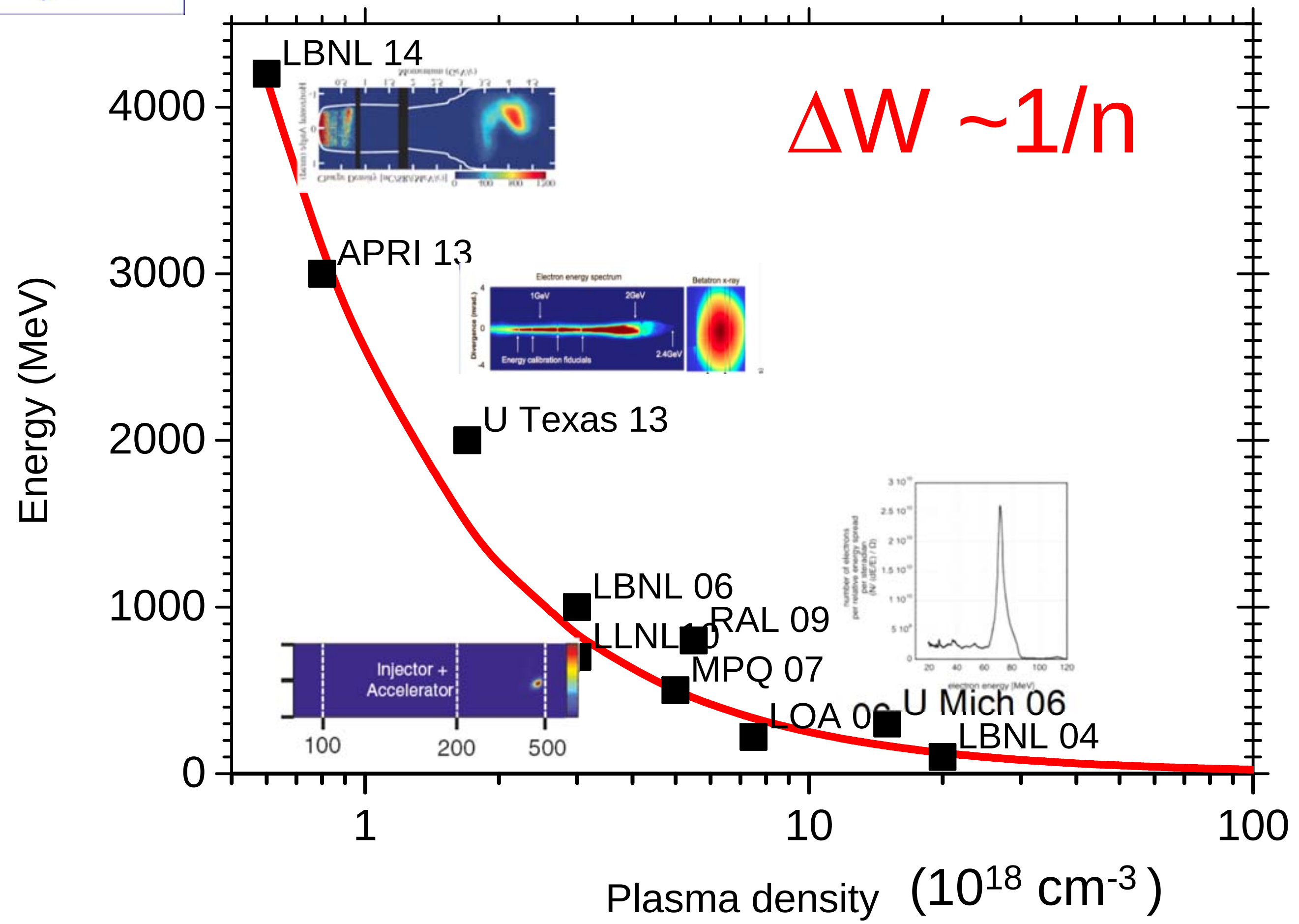
$\gamma_p \sim (n_c/n_e)^{1/2}$

$\gamma_p = \lambda_p / \lambda_0$

$L_a < L_{deph} = \lambda_p\, \gamma_p{}^2$

n_e	$10^{17} cm^{-3}$	$10^{19} cm^{-3}$
γ_p	100	10
L_a	1 m	1 mm
ΔW_{max}	20 GeV	200 MeV

Energy gain is large at low plasma density over a long distance



Non Linear regime with injection of plasma electrons

Energies above GeV reached for PW laser power: UTexas13, APRI13: 2 gaz jets

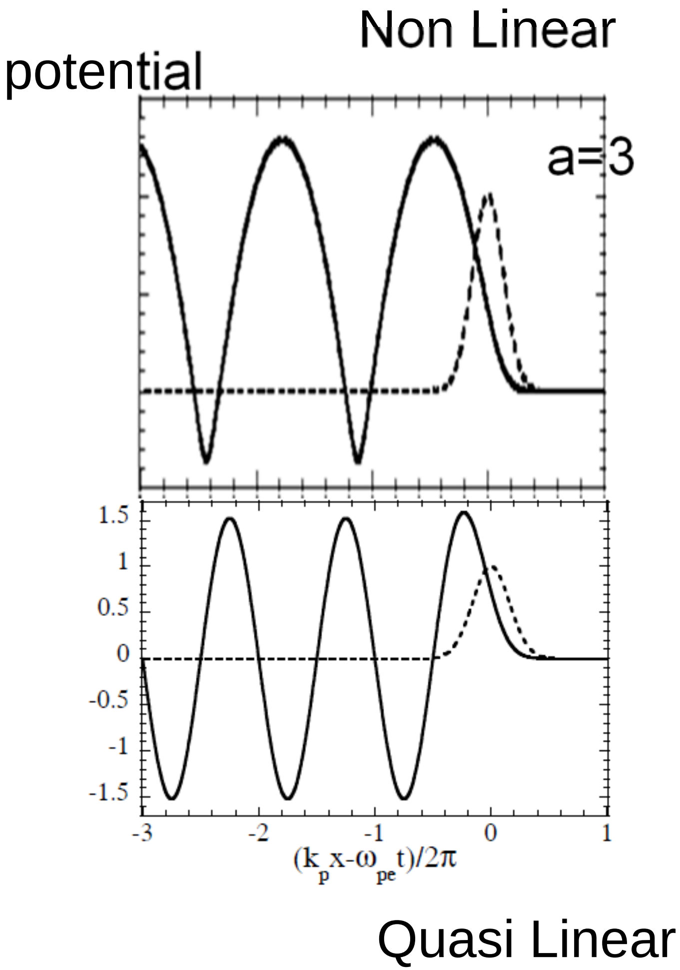
LBNL14 also includes channel guiding

- Energy increases for lower plasma density
- **At low enough density, self-injection stops, additional laser power or external injection should be used**

Constraints for good quality electron acceleration in LPA

- Electron beam must maintain with a small energy spread and emittance
  - Electrons submitted to the same accelerating field, micron cube volume
  - energy spread compensated during the process of acceleration
- Electron and accelerating field must travel together over a long distance to gain significant energy:
  - prevent laser diffraction →laser guiding,
  - prevent laser depletion → favor quasilinear regime
  - control plasma electron density (energy gain proportional to $1/n_e$)

Trapping of electrons in a plasma wave



- **External electrons** can be injected and trapped in a plasma wave either in the linear regime or non linear regime
- **Electrons from the plasma** can be trapped in the plasma wave in extreme non linear regime, leading to **wavebreaking**

Electron trajectories in the wakefield can be calculated in 1D

$$\frac{dp}{dt} = e\frac{\delta\Phi}{\delta z} - \frac{m_e c^2}{2\gamma}\frac{\delta a^2}{\delta z} \qquad (1)$$

Equation of motion along propagation direction, p is electron longitudinal momentum

$$p = m_e \gamma \beta c \qquad (2)$$

$$\gamma = (1 + \frac{p^2}{m_e^2 c^2} + a^2)^{1/2} = (\frac{1+a^2}{1-\beta^2})^{1/2} \qquad (3)$$

Variation of electron energy

$$m_e c^2 \frac{d\gamma}{dt} = v\frac{dp}{dt} + \frac{m_e c^2}{2\gamma}\frac{da^2}{dt} \qquad (4)$$

Assuming a dependence $z - v_p t$

$$\frac{d}{dt} = (v - v_p)\frac{\delta}{\delta z} \qquad (5)$$

Energy conservation in the frame moving at v_p

$$\frac{d}{dt}(m_e c^2 \gamma - v_p p - e\Phi) = 0$$

Electron trajectories in the wakefield can be calculated in 1D

$$\frac{d}{dt}(m_e c^2\gamma - v_p p - e\Phi) = 0 \qquad (6)$$

After integration and dividing by $m_e c^2$

$$\gamma(1-\beta_p\beta) = \phi + C \qquad (7)$$

C is a constant of integration

Normalized potential $\phi = e\Phi/(m_e c^2)$

After a Lorentz transform
(prime is moving frame)

$$z' = \gamma_p\left(z - v_p t\right),$$
$$\gamma' = \gamma\gamma_p(1-\beta\beta_p),$$
$$\gamma'\beta' = \gamma\gamma_p(\beta-\beta_p),$$
$$\phi' = \gamma_p\phi,$$
$$a' = a,$$

$$\gamma' = \phi' + C',$$

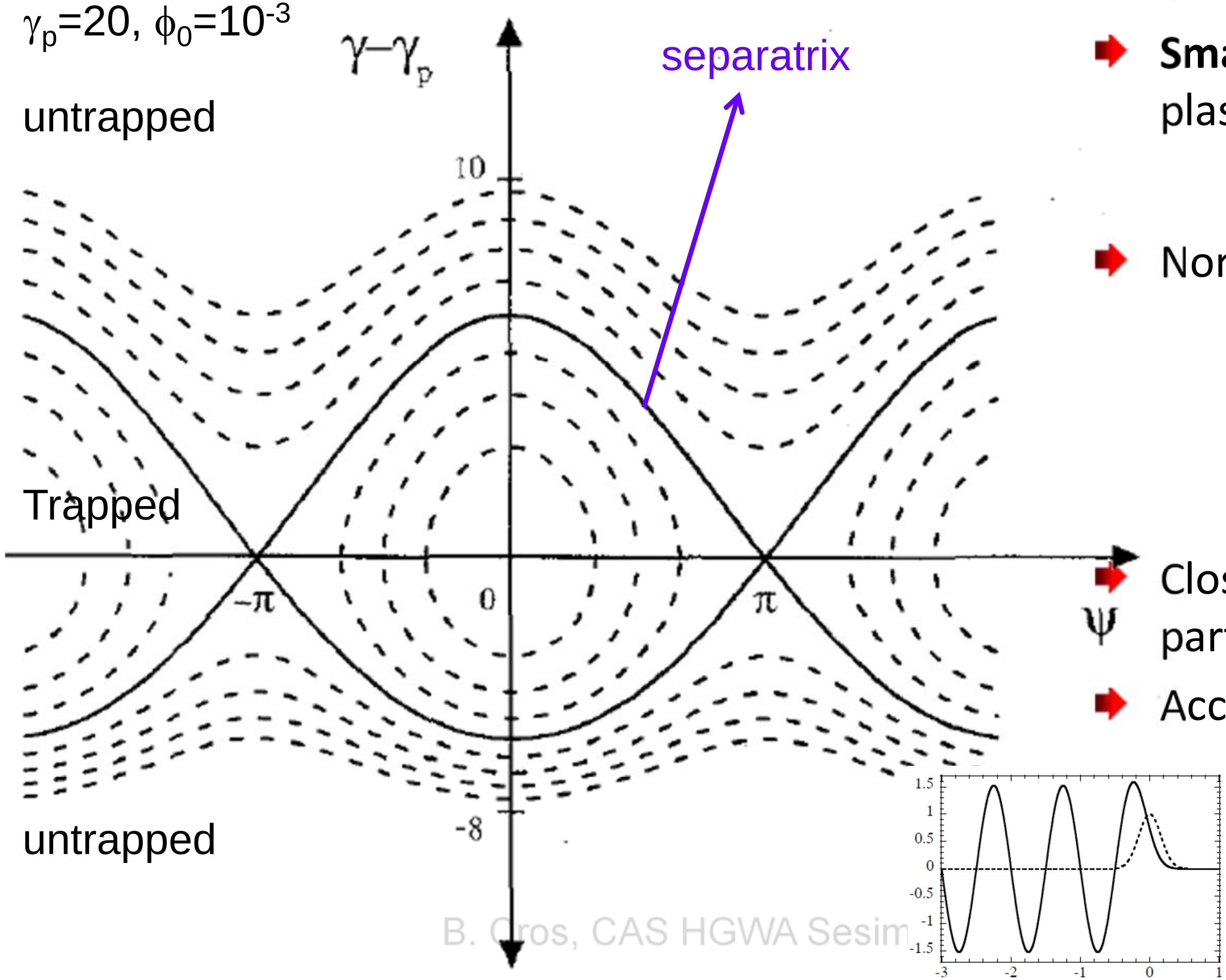
$$\gamma = \gamma'\gamma_p(1+\beta'\beta_p),$$
$$\gamma\beta = \gamma'\gamma_p(\beta'+\beta_p),$$

Trajectories are obtained from relations above for a given set of a^2 and ϕ

After the laser pulse $a^2 = 0$

Electron trajectories in 1D linear plasma wave

γ_p=20, ϕ_0=10^{-3}



- Orbits in **phase space** (γ, ψ)
- **Small amplitude** sinusoidal plasma wave

$$E_z = E_{max} \sin \psi$$

- Normalized potential

$$\phi = \phi_0 \cos \psi$$

$$\psi = k_p(z\_v_p t)$$

$$\phi_0 = E_{max}/k_p$$

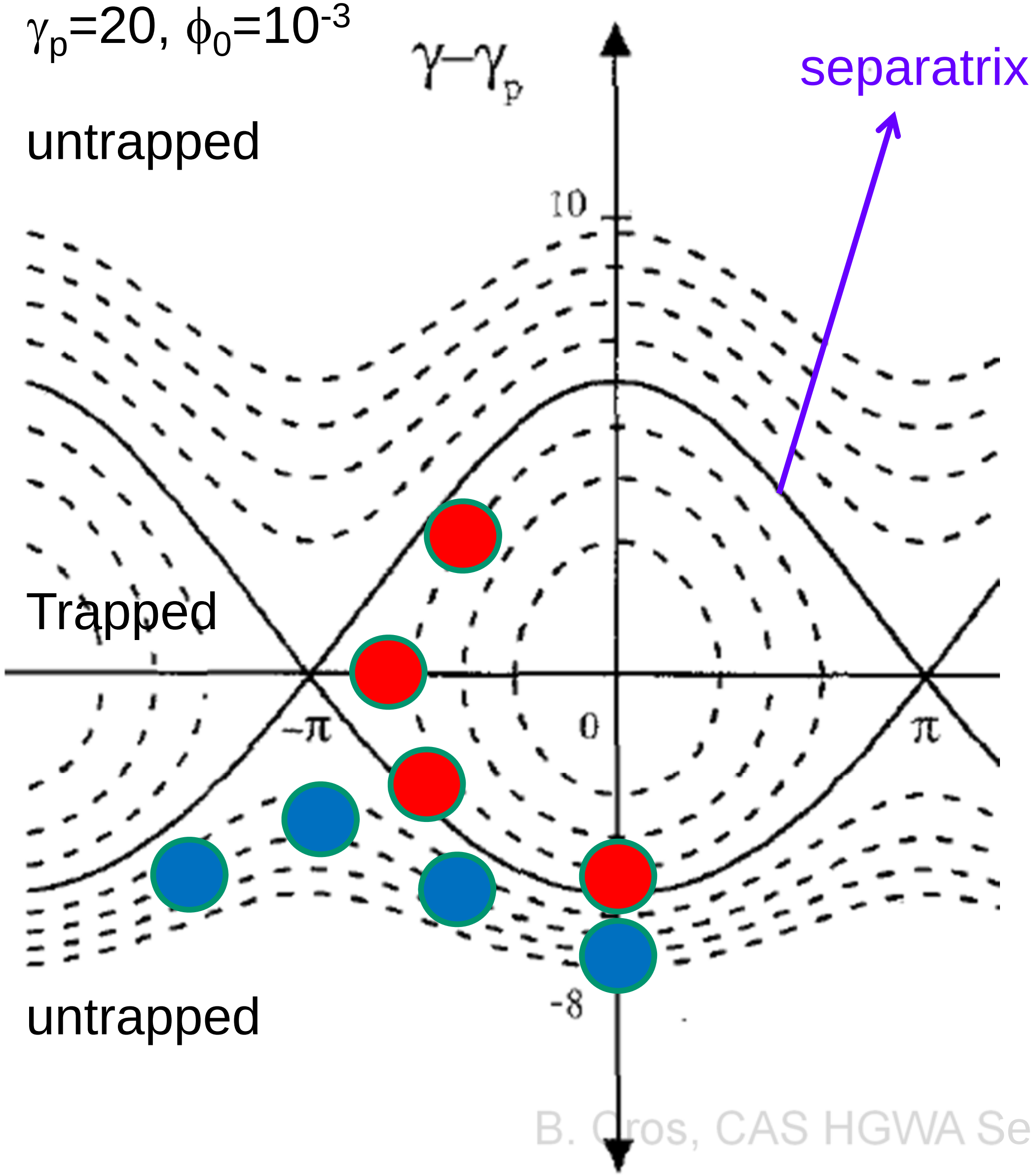
- Closed orbits=> trapped particles
- Acceleration for

$$-\pi < \psi < 0$$

Electron trapping depends on its initial velocity

γ_p=20, ϕ_0=10^{-3}

untrapped



untrapped

- Plasma Electrons with

  $v_z < v_p$ at $\psi = 0$

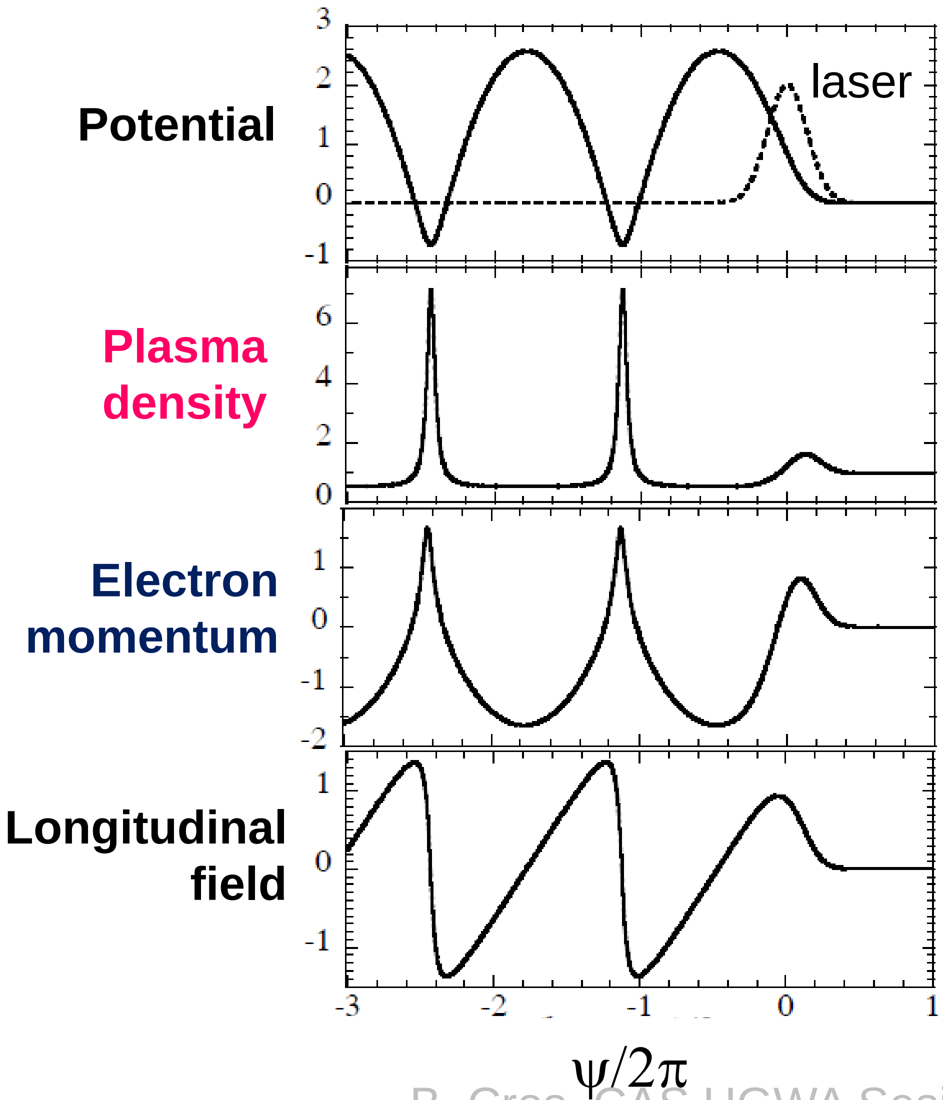
  are **slipping backward** with respect to plasma wave

- Electron with v_z too low does not gain energy and reaches $\psi = -\pi$ with $v_z < v_p$ ➔ remains **untrapped**

- Electron with high enough velocity such that

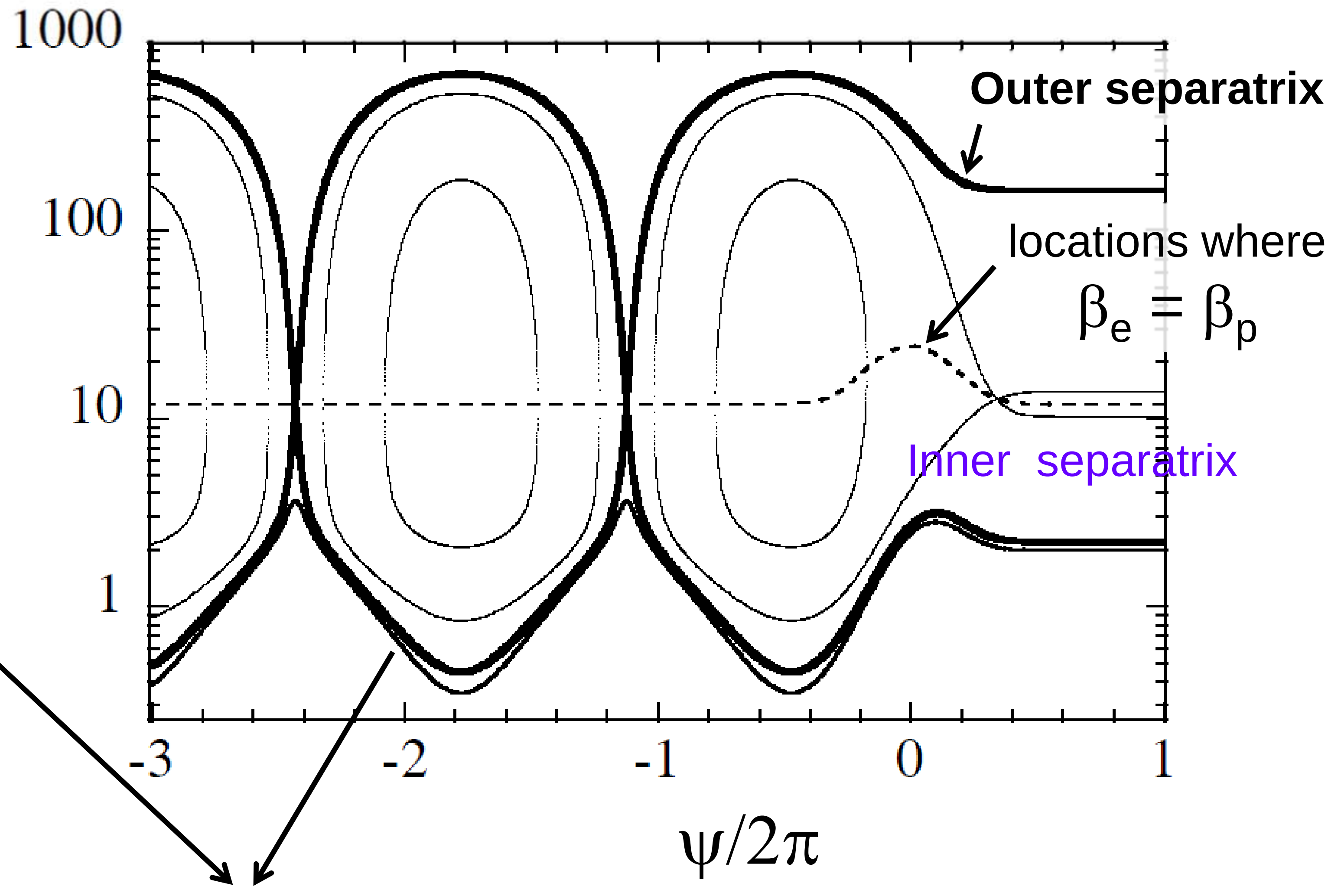
  $v_z > v_p$ as ψ ➔ $-\pi$ are **trapped**

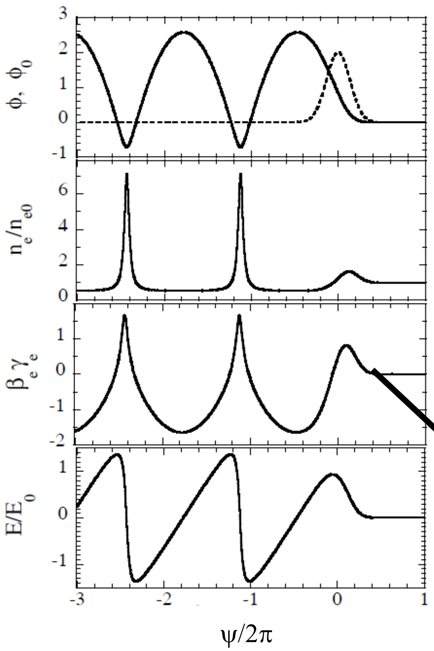
Extreme non linear amplitude leads to wavebreaking



- Density exhibits spikes/plateau along the propagation direction
  - $n_e/n_0 = \beta_p/(\beta_p-\beta_e)$
- When electron velocity approaches the phase velocity, n_e approaches infinity
  - definition of wavebreaking
  - also a condition for trapping

Electron trajectories in the NL regime facilitate trapping





Plasma electrons initially at rest

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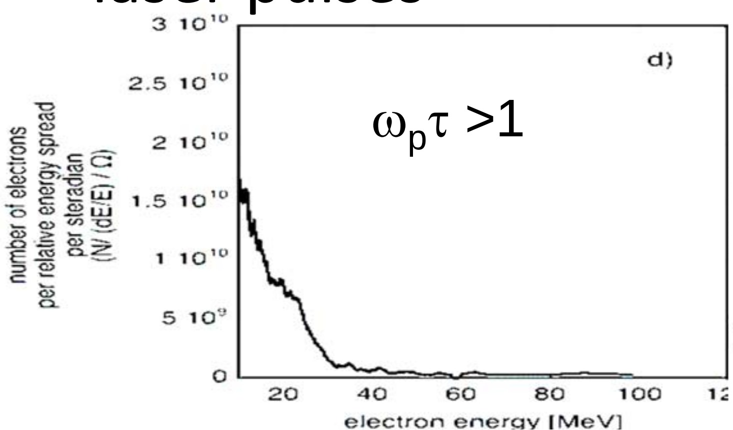
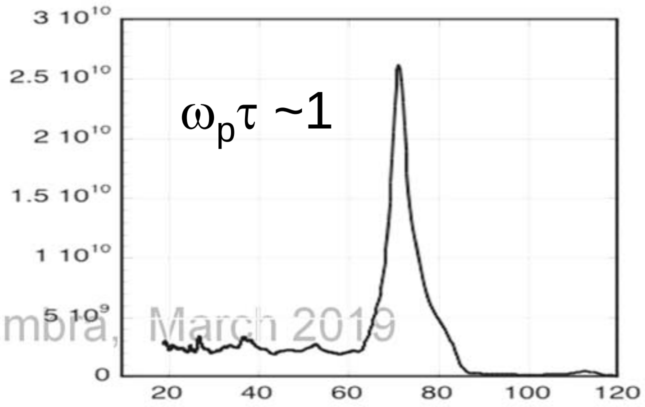
Several methods leading to electron trapping in plasma waves

- Self-modulated wakefield (long pulses)
- External injection possible in QL or NL wakefield
  - close to resonant duration ($\omega_p\tau \sim 1$),
  - In addition self-injection in the bubble regime
- 2 types of methods:
  - Local perturbation of QL wakefield
  - Global and NL evolution of the wakefield structure

For several years LWFA has relied on self injection with long pulses ($\omega_p\tau > 1$)

- Self injection of electron heated during the interaction of laser pulse and plasma wave,
- Small energy gain (10 MeV) due to a short dephasing length (50 µm).
- Large energy spread (exponential distribution) due to continous injection
- Out of resonance operation: reduced efficiency
- Significant progress followed the availability of short laser pulses





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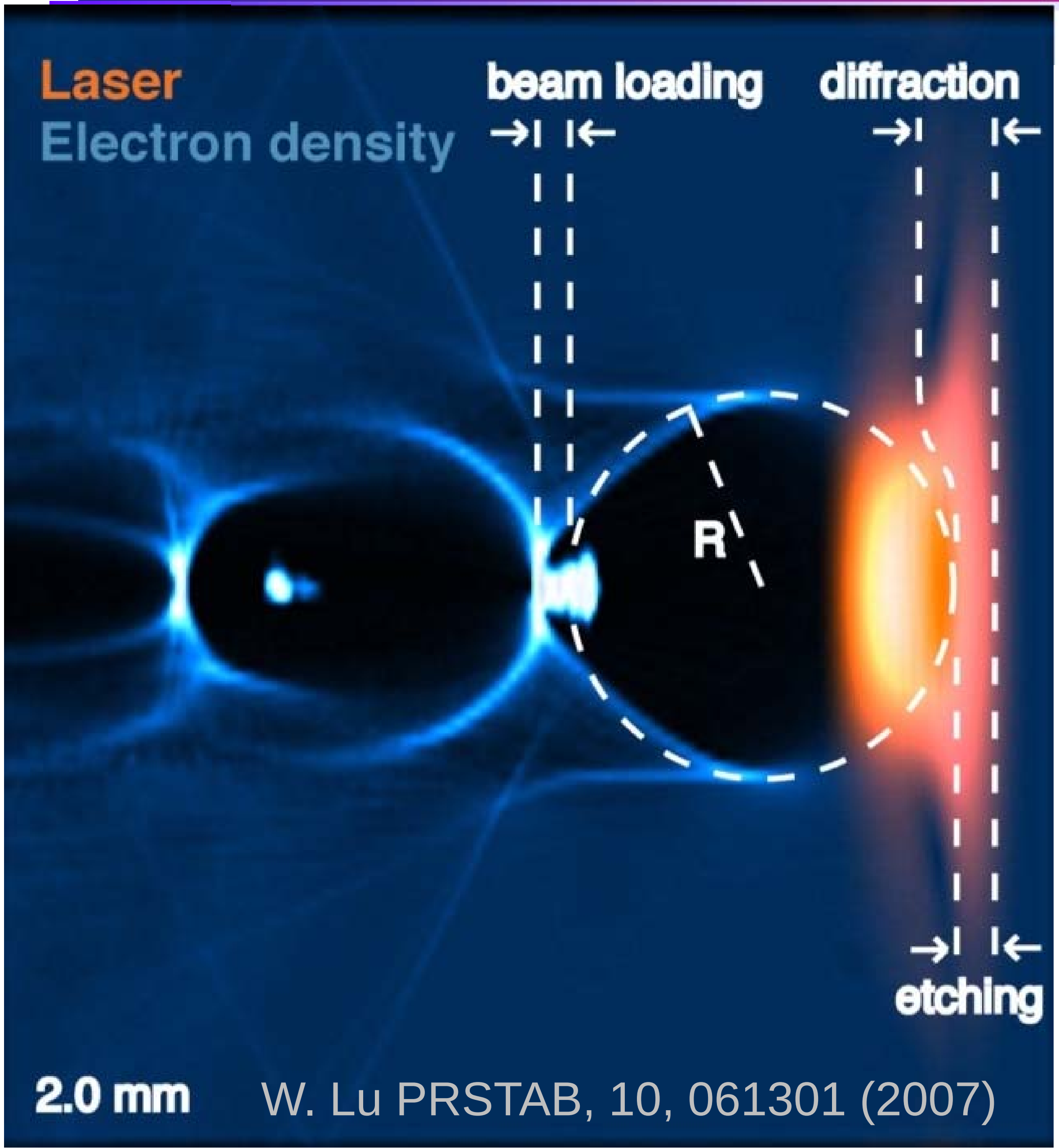
Self injection of electrons in a plasma cavity



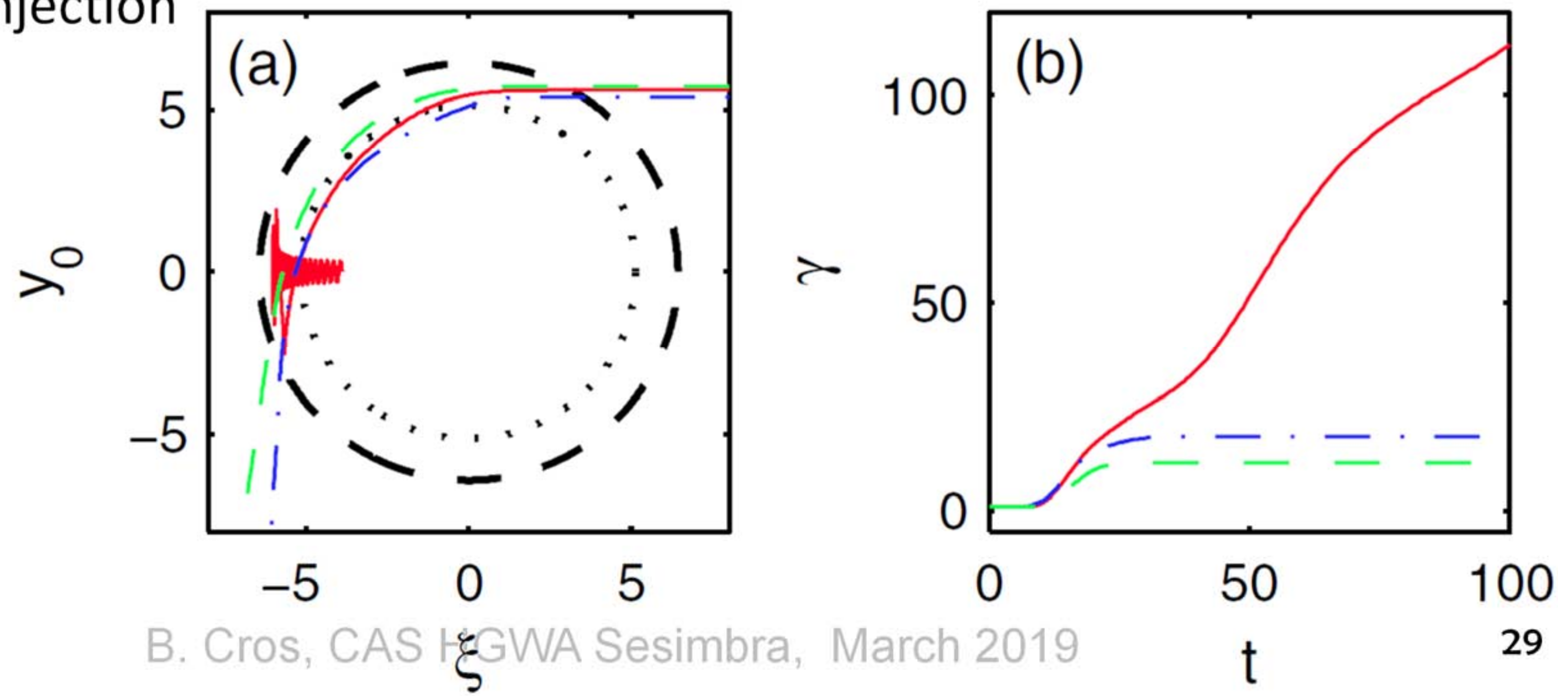
$a_0 > 2$

- Pulse compression and self-focussing
- Electrons are expelled from high laser intensity area and leave behind a cavity (bubble filled with ions)
- Electrons self-injected at the back of the bubble and accelerated
- Injected electrons modify the back of the bubble (beam loading)

Lu (2007), Pukhov (2002)

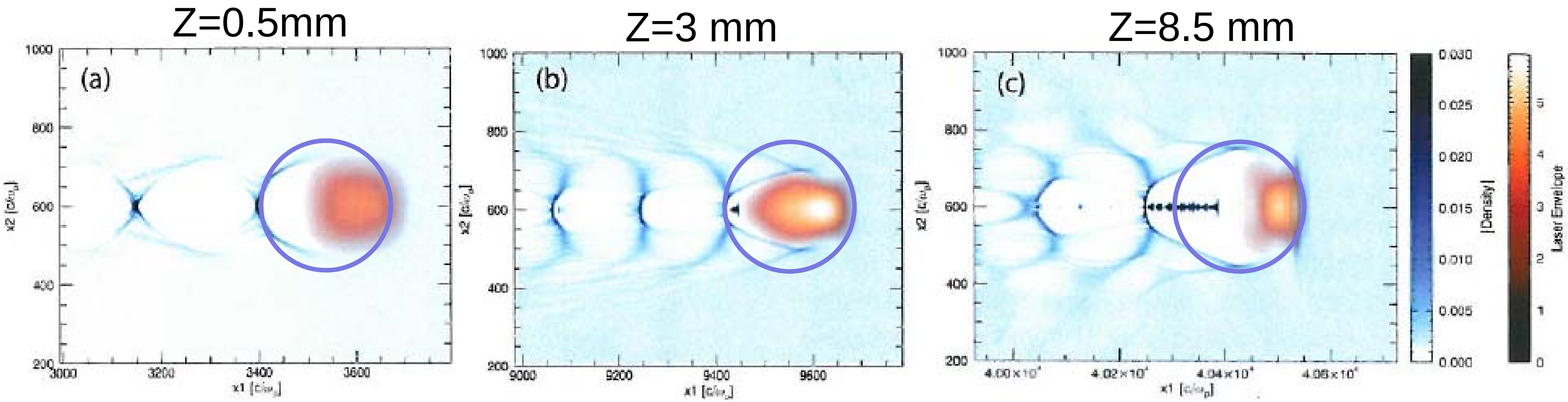
Electrons trapped and accelerated by an expanding bubble

- Analysed theoretically by Kalmykov et al, PRL 103, 135004 (2009)
- Electron trajectories calculated in the expanding bubble: electrons that would normally slip back can be trapped as the bubble radius changes (red curve)
- In this case bubble expansion is caused by defocusing
- Defocusing followed by focusing is proposed as a way to stop injection



Laser self-focusing leads to wake deformation

Laser propagation →



Laser volume nearly matched to the cavity

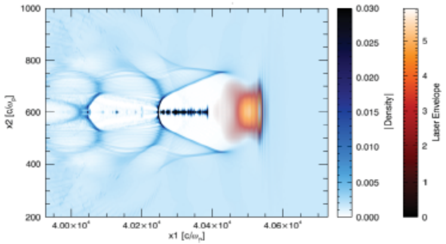
First injection after over focusing and intensity increase

After multiple injection and dephasing, back of cavity has slown down

Example from Froula PRL 2009

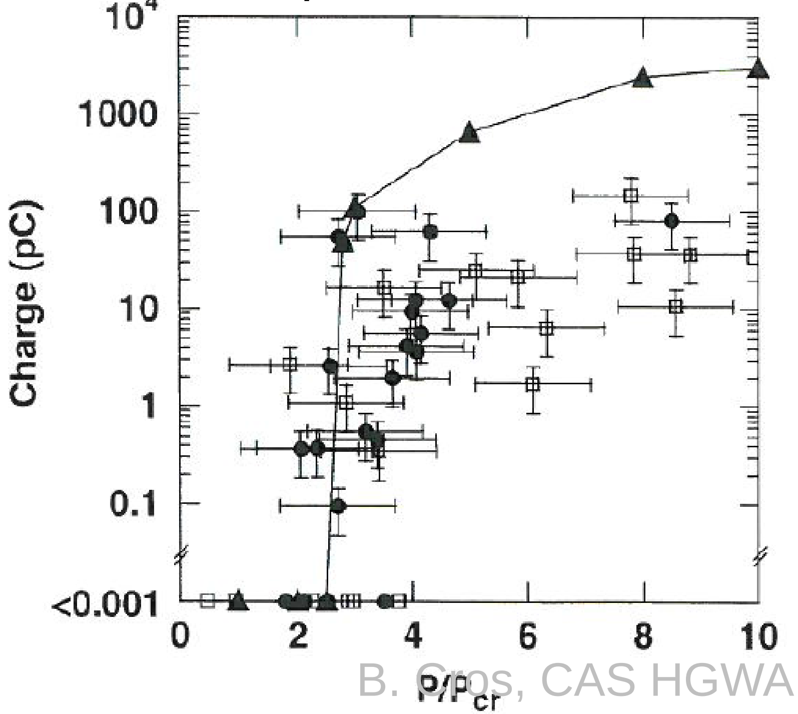
Froula PRL 103, 215006 (2009), see also Mangles et al, PRSTAB 15, 011302 (2012)

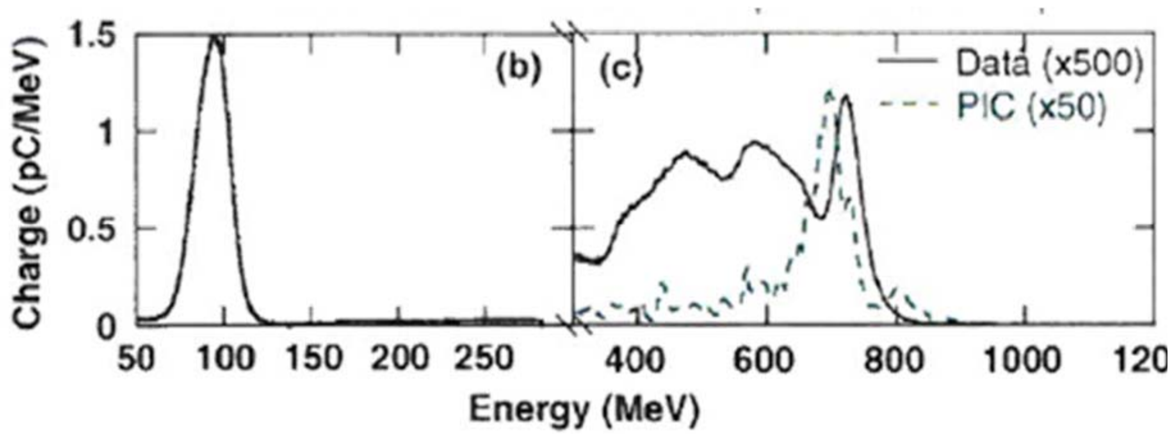
Demonstration of injection linked to self-focussing threshold



- Injection of electrons occurs continuously , unless trapping conditions evolve due to changes in the laser amplitude or plasma stop it

Charge above 250MeV measured for density 3- 5 $10^{18}cm^{-3}$+pic simulations





- Self focussing plays a key role and determines the laser power at threshold

Improvement needed

- Self-injection is easily achieved but:

- Huge number of electrons make the process noisy
- « beam quality » not good sometimes undefined
- Unstable as operation is close to the threshold (a small fluctuation of inital parameters produces large variations)

End of part 1

- Methods to control electron injection are discussed in part 2

Electron sources from plasma part 2

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Image USAF 050118-F-3488S-003

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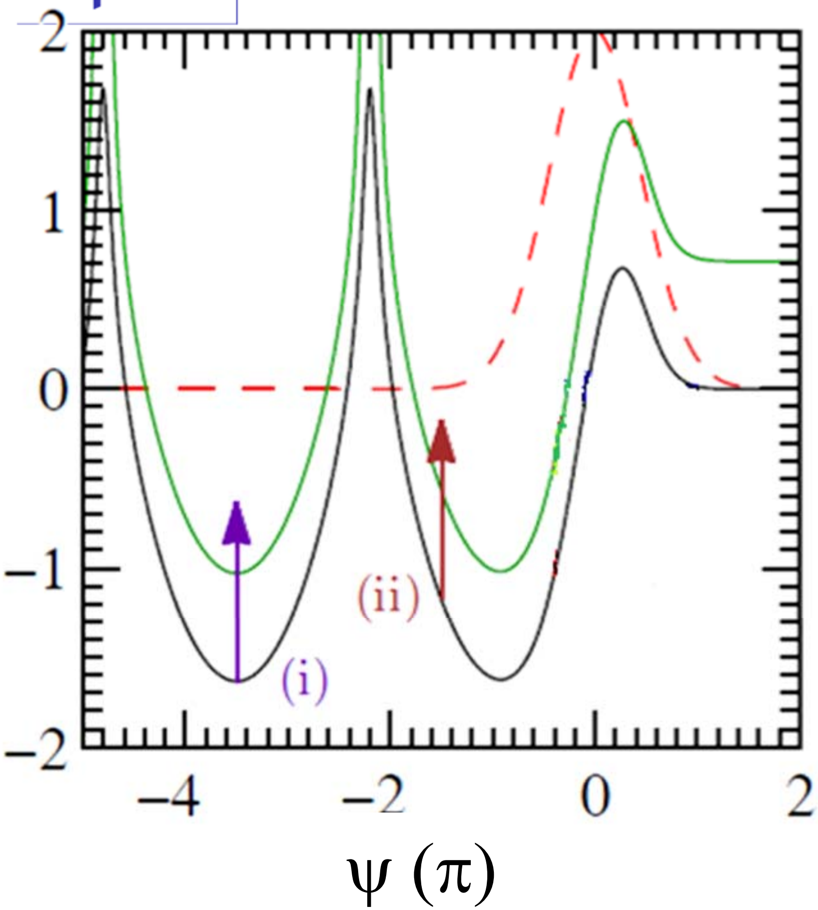
Additional laser beam creates a local perturbation of QL wakefield

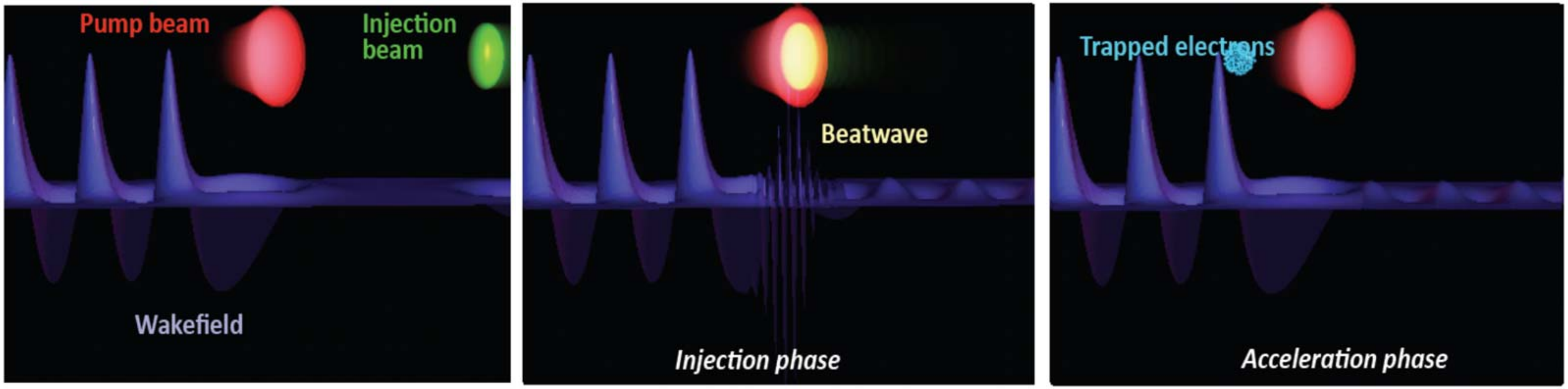


- (i) **Ponderomotive injection**: uses additional pulse to kick plasma electrons and place them on a trapped orbit
- (ii) **colliding injection pulses** or ionising pulse

These methods require < micron precision and stability, challenging to implement

Low charge correleted to beam quality

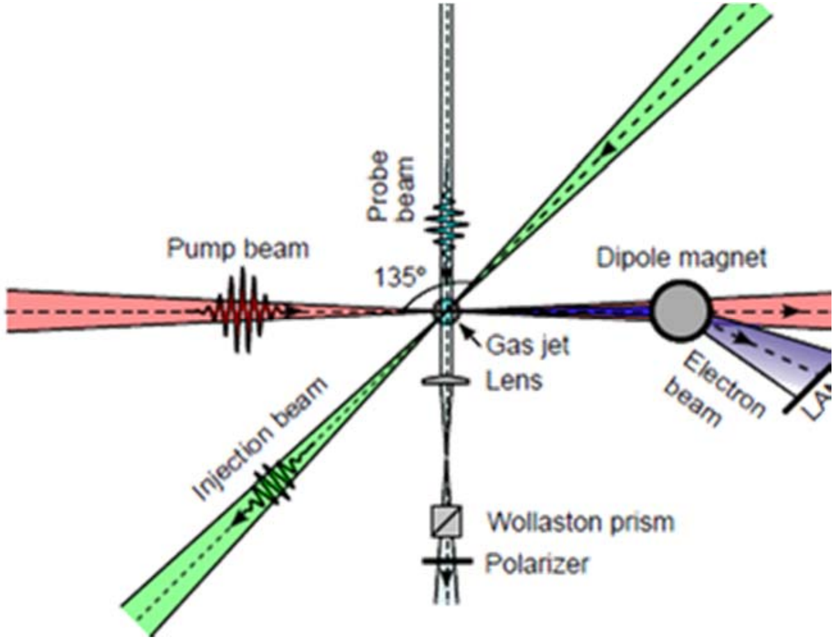
Use an additional laser pulse to create electrons in situ

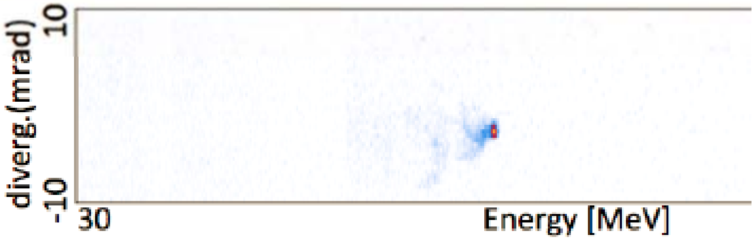


- Colliding pulses: use the beating of two laser pulse to control electron injection, injection condition satisfied only when they beat, small volume, < pC level, 1% energy spread

J. Faure *et al.*, Nature (2006)
C. Rechatin *et al.*, PRL (2009)
see also Faure, proceedings of CAS 2014

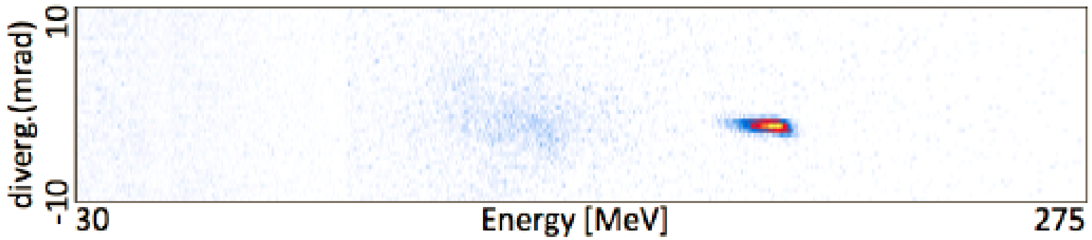
Moderate laser intensity, good quality and stability required

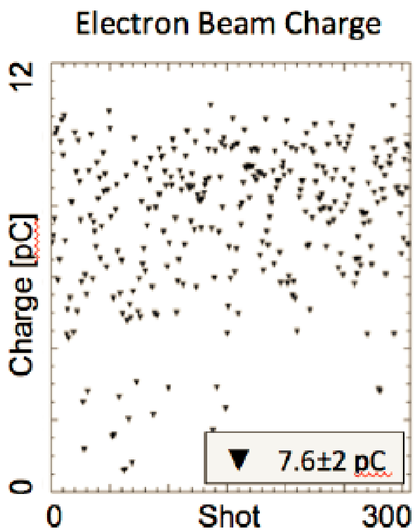


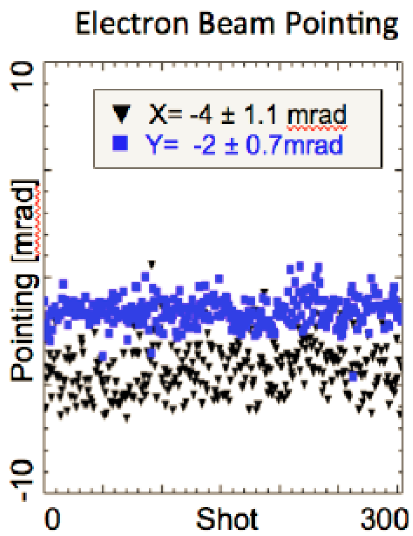


150 MeV instrument-limited 1.4% FWHM energy spread

Best result







CPI in gas jet
$a_0 = 1.2$ & 0.6
$n_e \sim 10^{19} cm^{-3}$

Geddes et al. AIP Conference Proceedings, 1777(1):040003, 2016.

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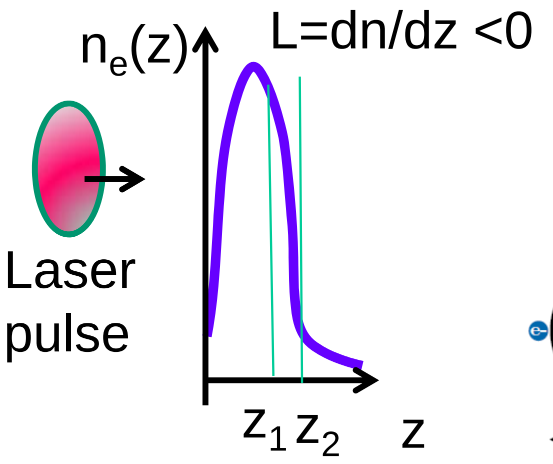
Acting on the plasma to control injection

- Tailoring the density profile
  - Step like density profile
  - Smooth density decrease
- Different gas species

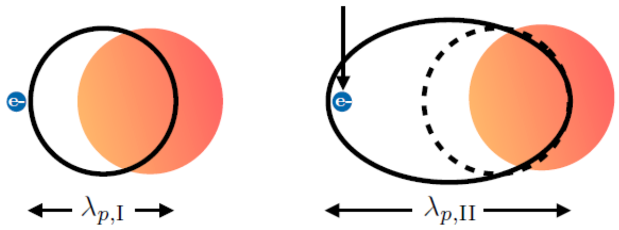
Injection with negative density gradient



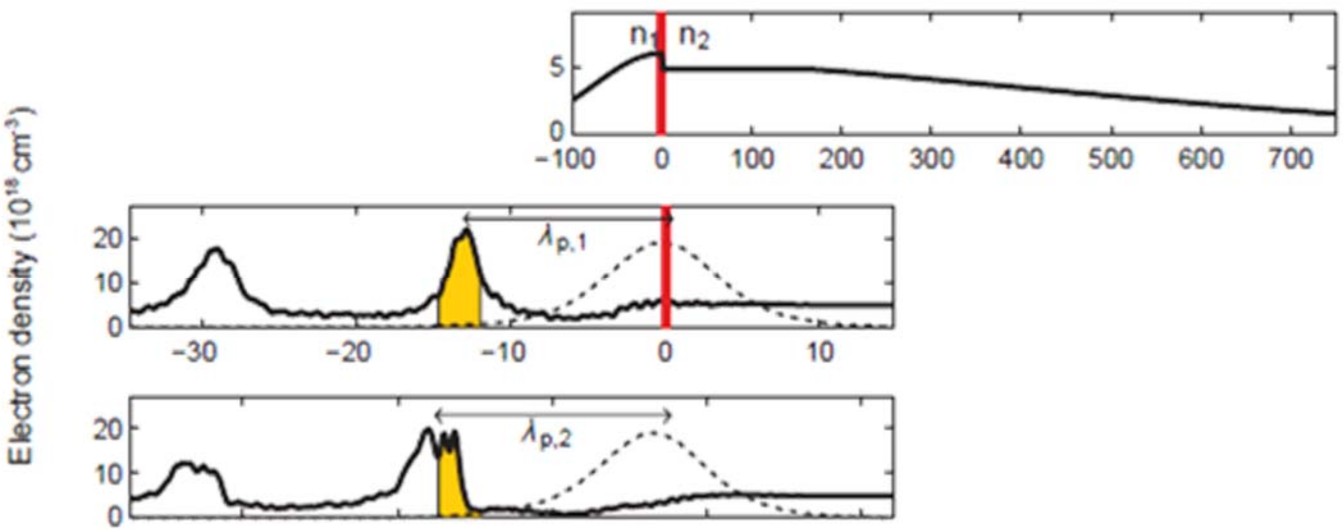
$$\lambda_p(z) \sim 33\ [n(z)]^{-1/2}$$

$$\lambda_p(z_2) > \lambda_p(z_1)$$

the plasma wavelength increases with decreasing density

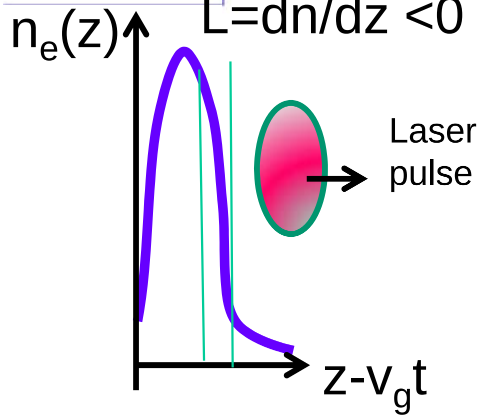


- The back of the wake slows down as the laser propagates down the gradient
- This reduces the trapping threshold
- Trapping can be confined to a small region in the gradient area



Schmid et al, PRAB, 13, 091301 (2010)

Phase velocity of the plasma wave in a density gradient



- 1D quasi linear regime, quasi static approximation

- Potential of a sinusoidal plasma wave in a density gradient

$$\phi = \phi_0(z)\sin\psi(z)$$

- Phase

$$\psi(z) = k_p(z)(z - v_g t)$$

- Frequency

$$\omega = -\delta_t \psi = k_p(z) v_g$$

- Wave number

$$k = \delta_z \psi = k_p(z) + (z - v_g t)\delta_z k_p(z)$$

- **In a negative density gradient, phase velocity decreases as time increases**

$$v_p(z,t) = \omega / k = \frac{v_g}{1 + (z - v_g t)\delta_z k_p / k_p}$$

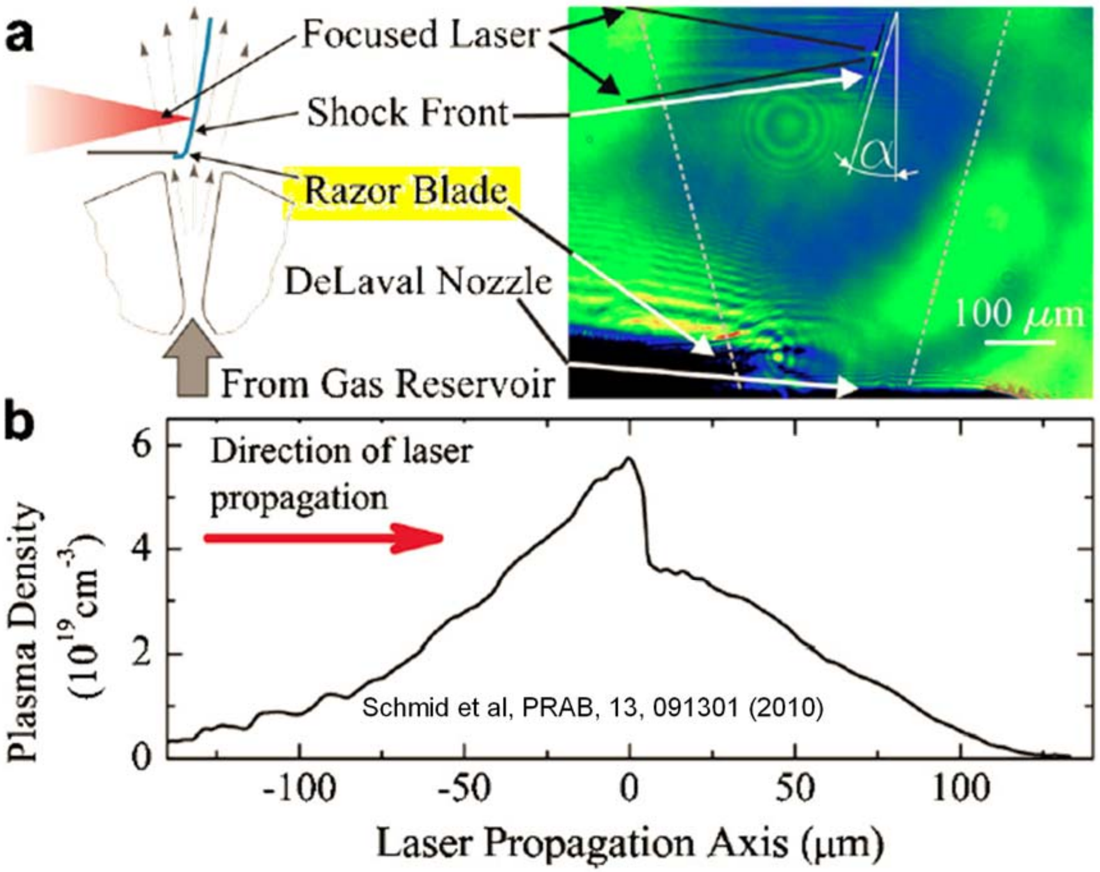
$(z - v_g t)$: < 0 behind the laser

$\delta_z k_p / k_p$: < 0

Also true for smooth gradient

A sudden change in plasma density: practical aspects

- An object placed in the gas flow creates a shock associated to change of gas density over a short distance
- Laser ionisation occurs over a short time scale: the plasma profile follows gas profile



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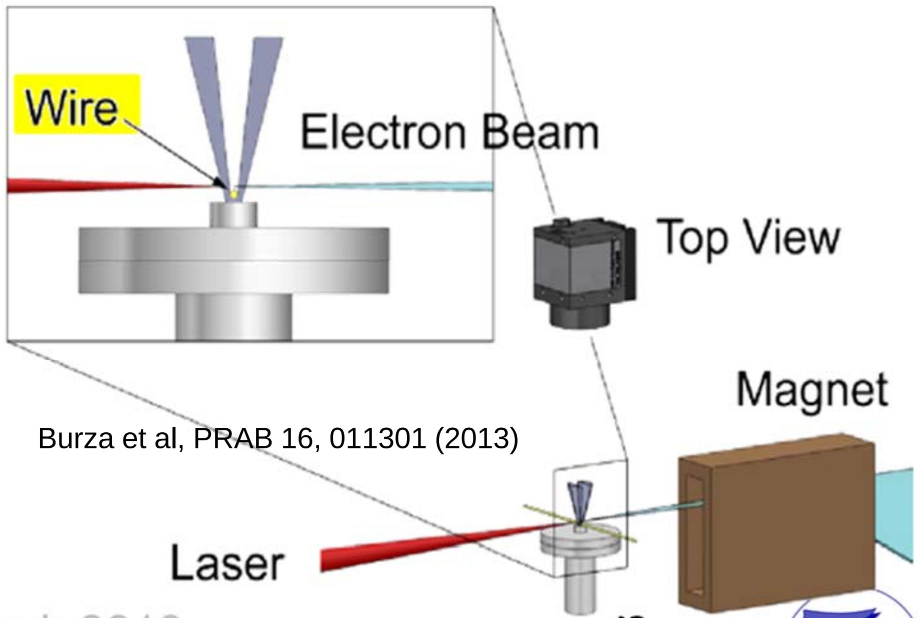
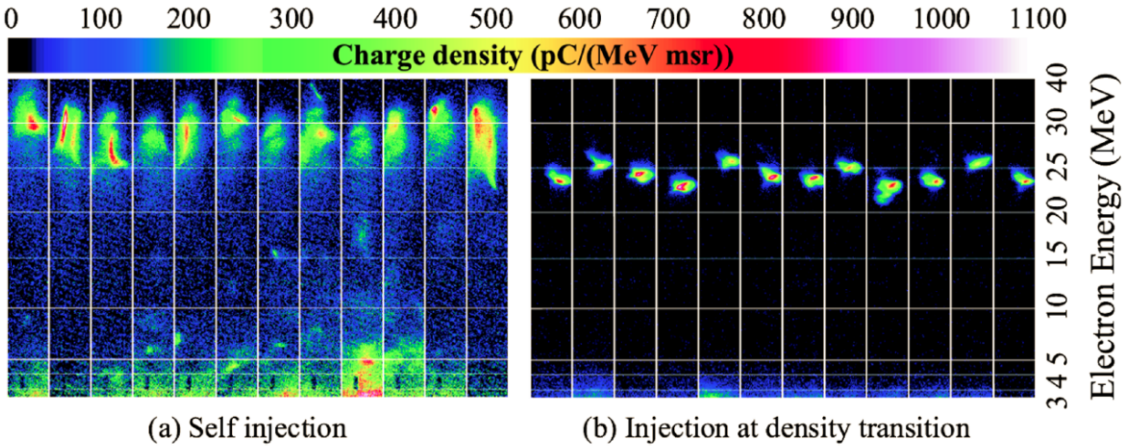


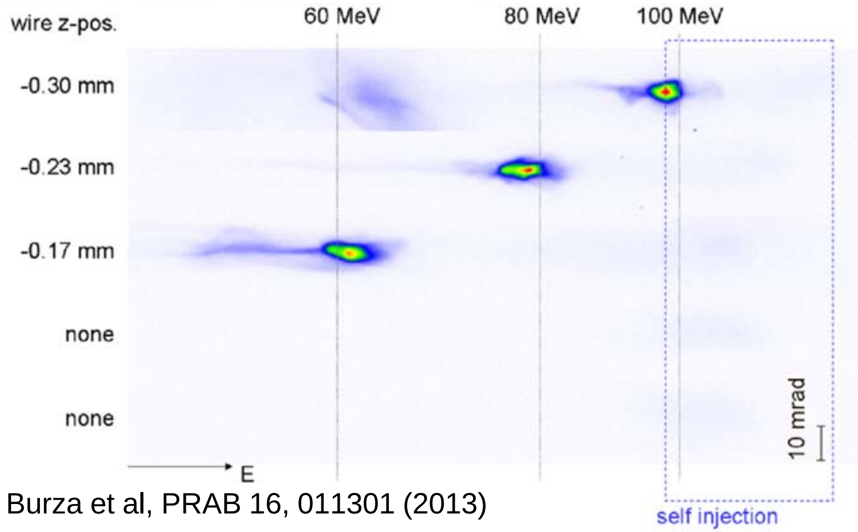
Burza et al, PRAB 16, 011301 (2013)

A sudden change in plasma density triggers and stops self-injection

Schmid et al, PRAB, 13, 091301 (2010)



(a) Self injection (b) Injection at density transition



Burza et al, PRAB 16, 011301 (2013)

- Accelerated electrons come out of the plasma with a smaller energy spread (« clean spectrum »)
- Energy can be tuned by changing blade/wire position

- Parameter set (Burza 2013)
  - $n_e \sim (6 \rightarrow 3) \times 10^{18}$ cm^{-3}
  - $E = 100$ MeV
  - $\frac{\sigma_E}{E} = 4\ \%$ (fwhm)
  - $Q \sim 43$ pC Total charge, charge in the peak not given

Use an additional atomic species to create electrons in situ

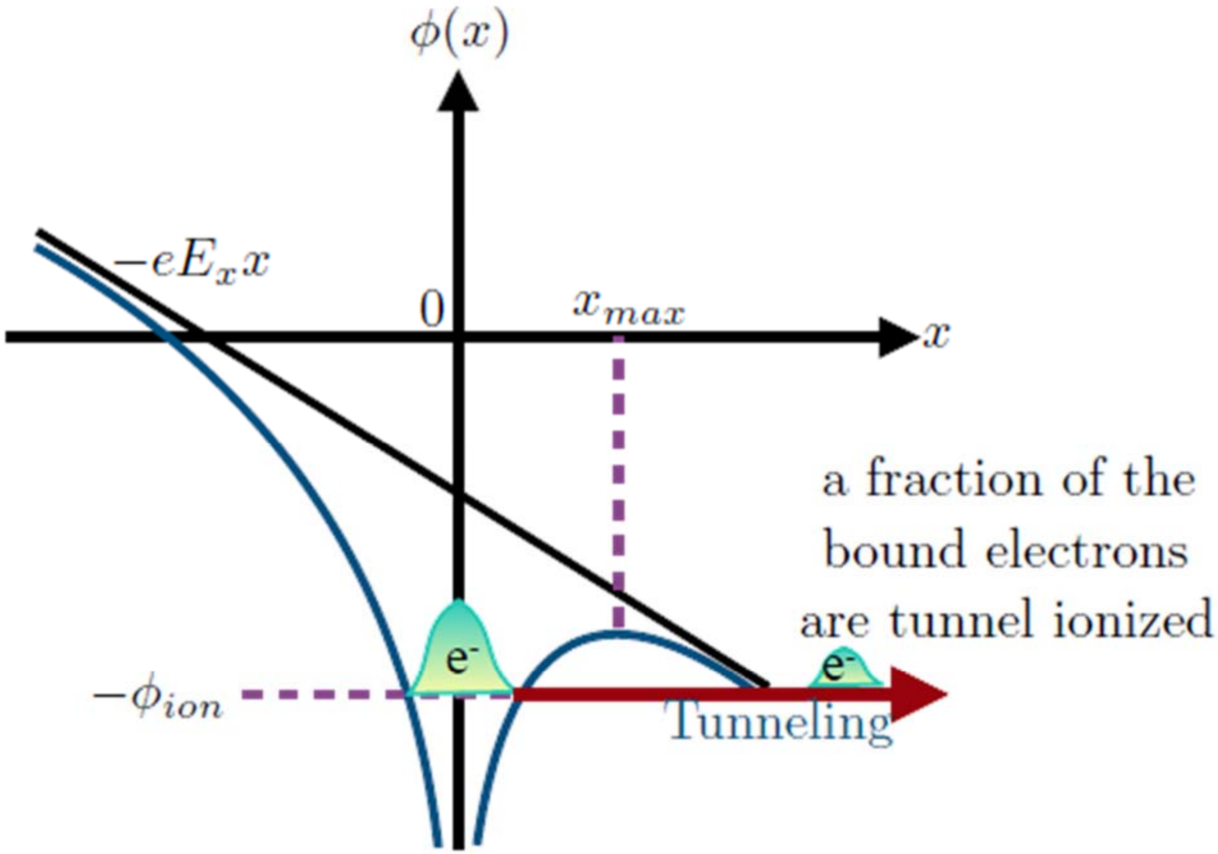
- Add small amount of gas with high atomic number

  example (99% H_2+1% N_2)

- Outer shell electrons of N_2 behave like electrons of H_2
- Inner shell electrons of N_2 are ionised close to the intensity peak

Tunnel ionisation occurs in the intense laser field

- Large amplitude laser field modifies the Coulomb potential and bound electrons can tunnel out



- This mechanism depends on the field strength and changes during the pulse, so that inner electrons can be freed if peak intensity is large

Ionisation thresholds for several atomic species

Hydrogen

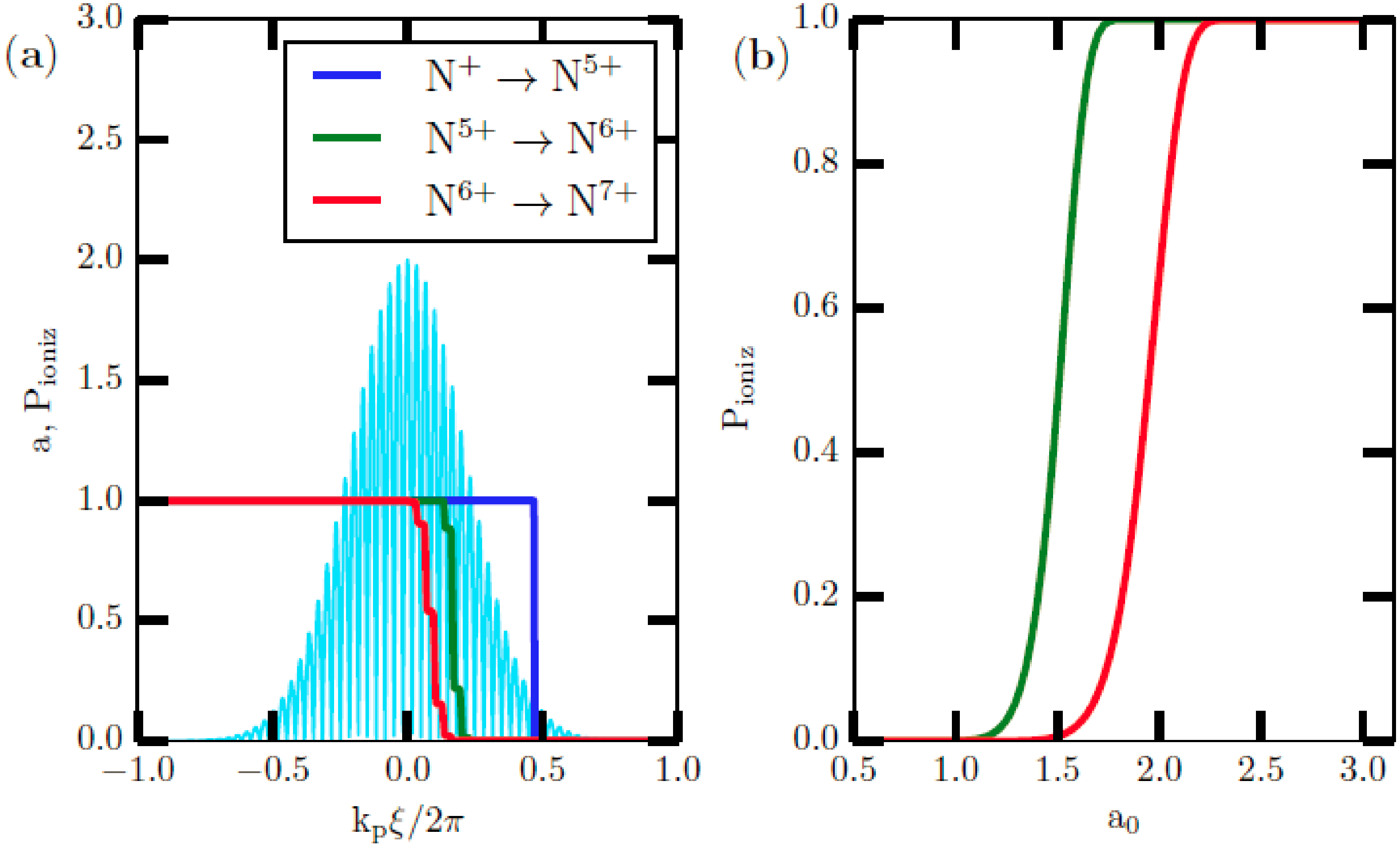
Nitrogen

Level	H	He	C	N	O
1	$1{,}4 \times 10^{14}$	$1{,}5 \times 10^{15}$	$6{,}5 \times 10^{13}$	$1{,}8 \times 10^{14}$	$1{,}4 \times 10^{14}$
2		$8{,}7 \times 10^{15}$	$3{,}5 \times 10^{14}$	$7{,}7 \times 10^{14}$	$1{,}5 \times 10^{15}$
3			$2{,}3 \times 10^{15}$	$2{,}3 \times 10^{15}$	$4{,}0 \times 10^{15}$
4			$4{,}3 \times 10^{15}$	$9{,}0 \times 10^{15}$	$9{,}0 \times 10^{15}$
5			$3{,}8 \times 10^{18}$	$1{,}5 \times 10^{16}$	$2{,}7 \times 10^{16}$
6			$6{,}4 \times 10^{18}$	$1{,}0 \times 10^{19}$	$4{,}0 \times 10^{16}$
7				$1{,}6 \times 10^{19}$	$2{,}4 \times 10^{19}$
8					$3{,}6 \times 10^{19}$

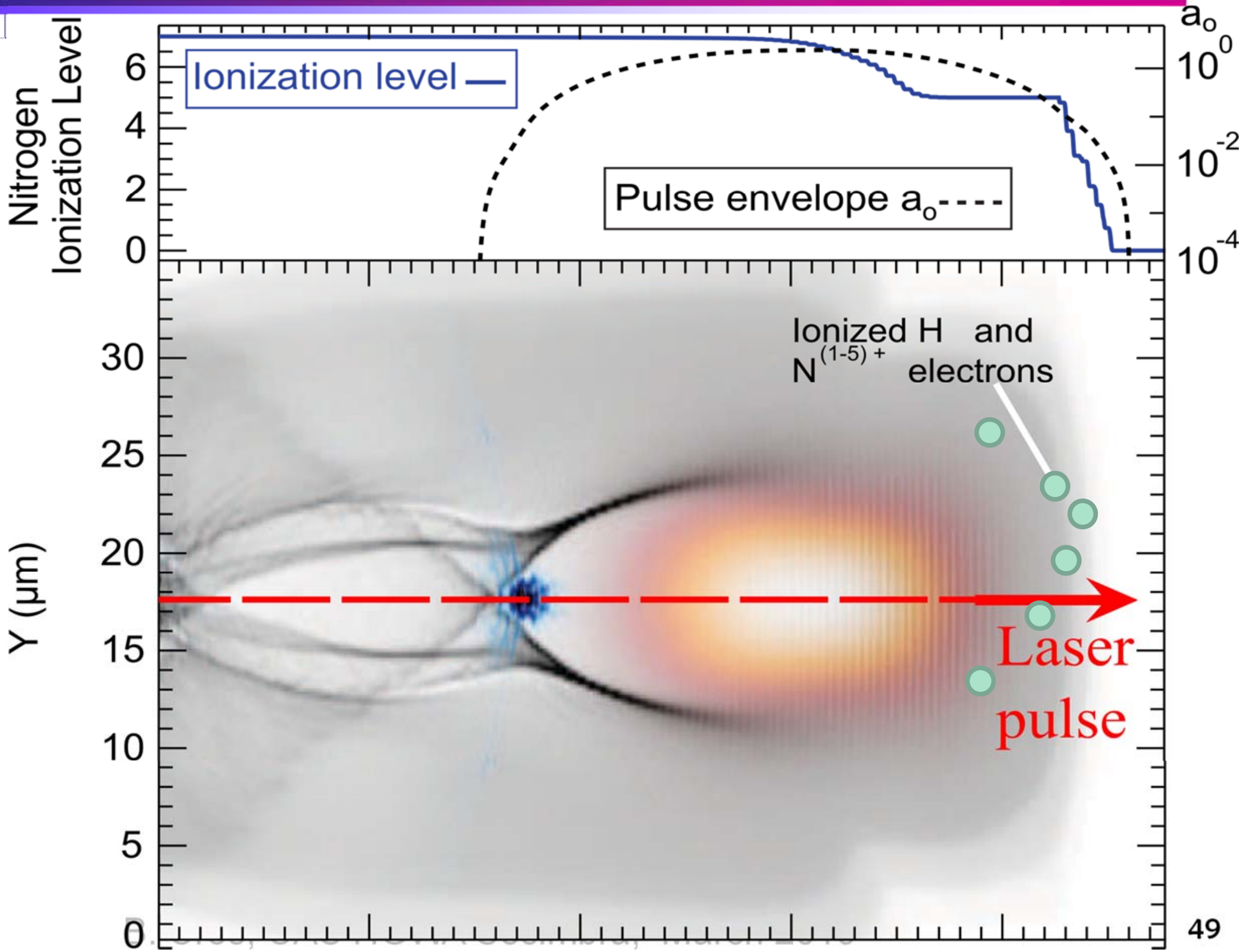
~10^3 factor between ionisation levels

Intensity in W/cm2

Ionisation probability grows with time in the pulse front edge

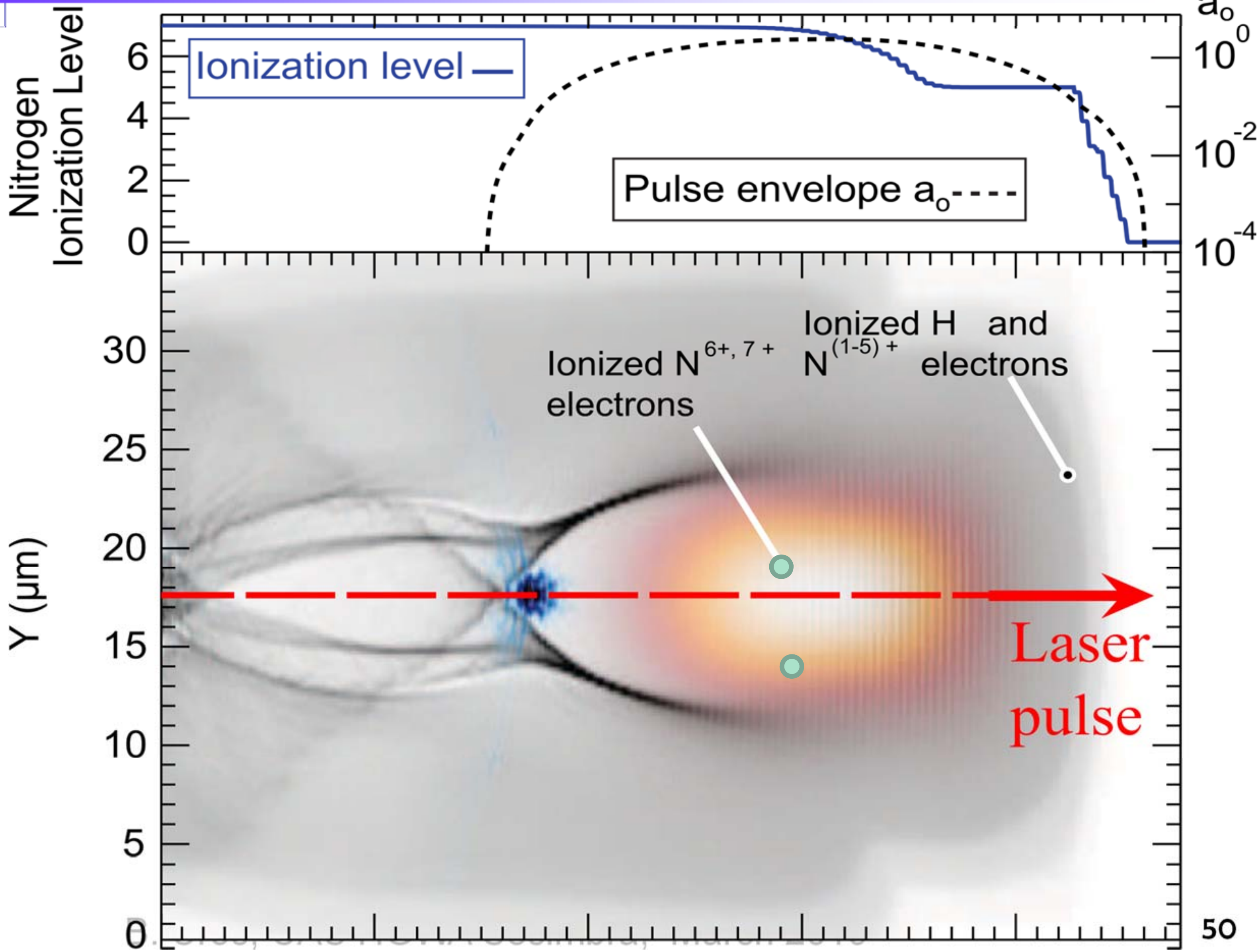


Ionisation of different levels follows the evolution of laser envelope



A. Pak *et al.*, PRL – **104**, 025003 (2010)

Ionisation of different levels follows the evolution of laser envelope



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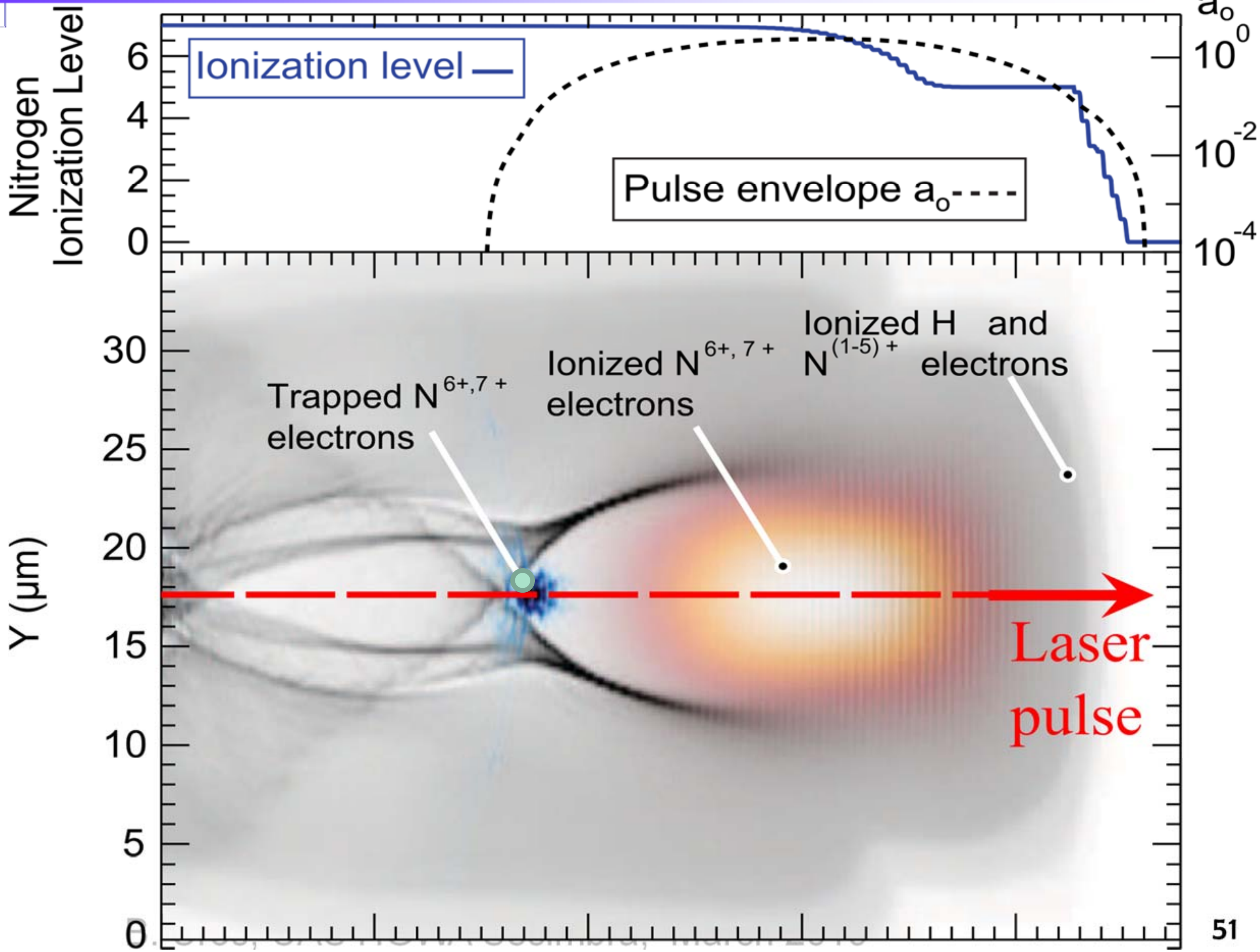
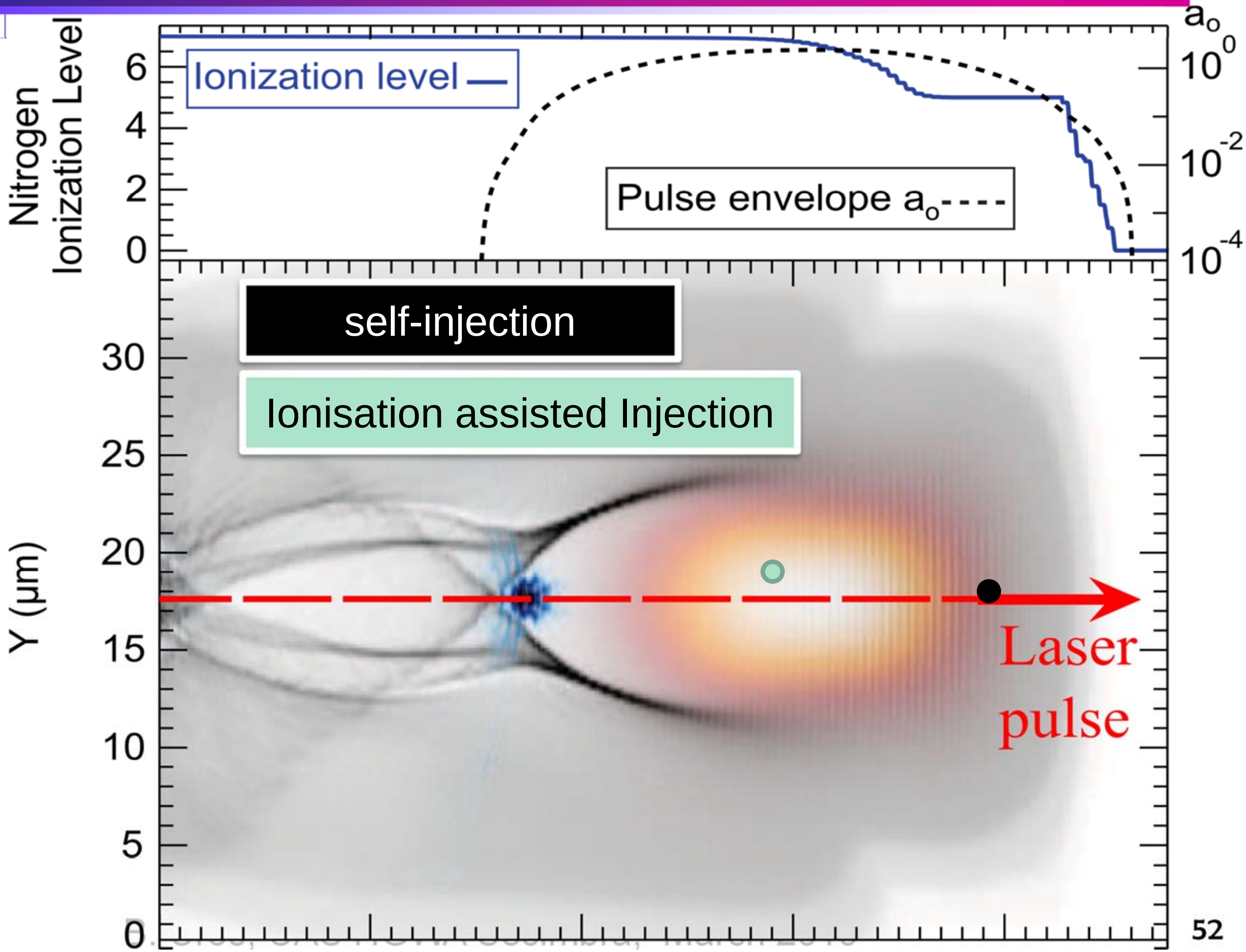
Ionisation of different levels follows the evolution of laser envelope



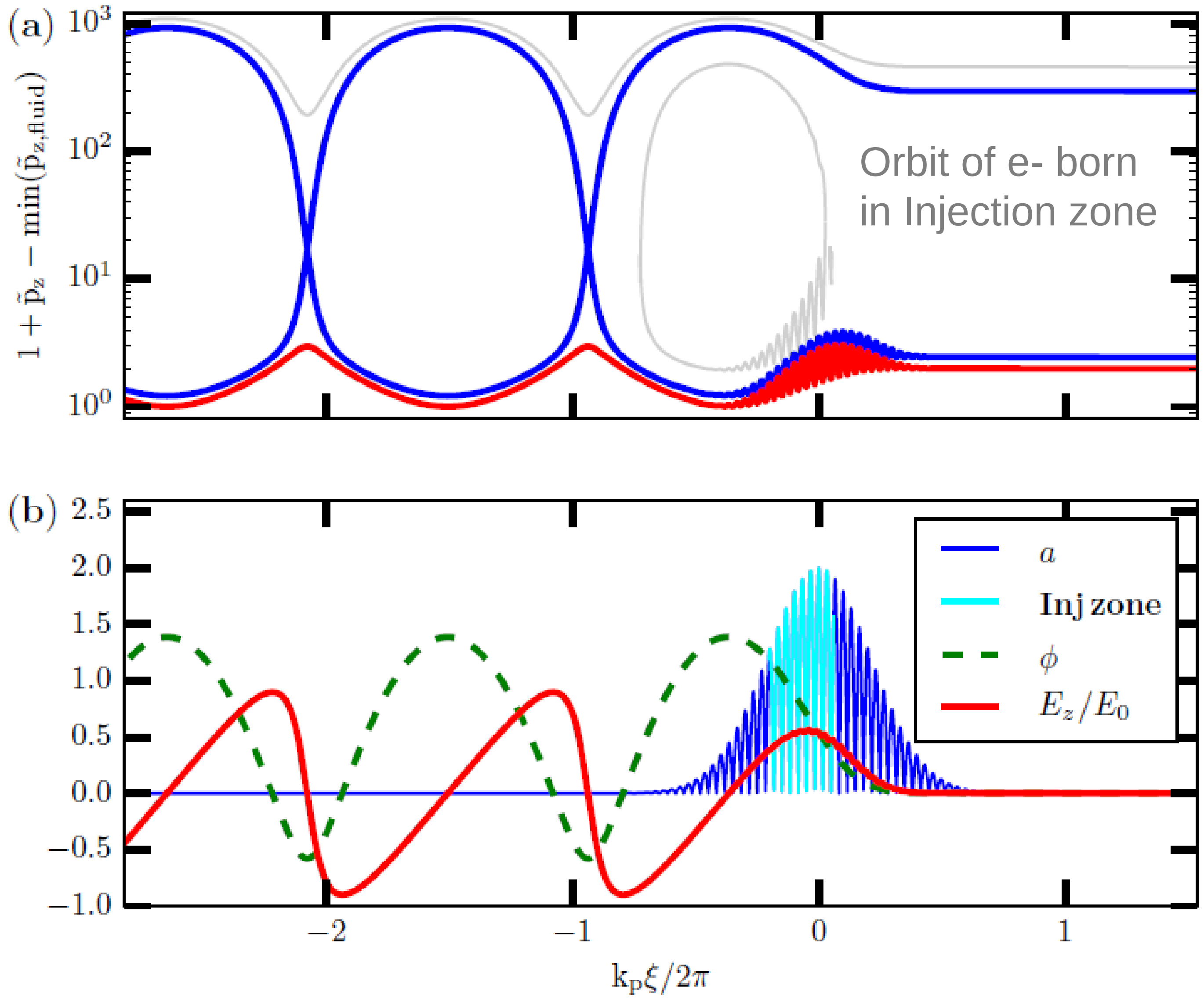
A. Pak *et al.*, PRL – **104**, 025003 (2010)

Ionisation of different levels follows the evolution of laser envelope

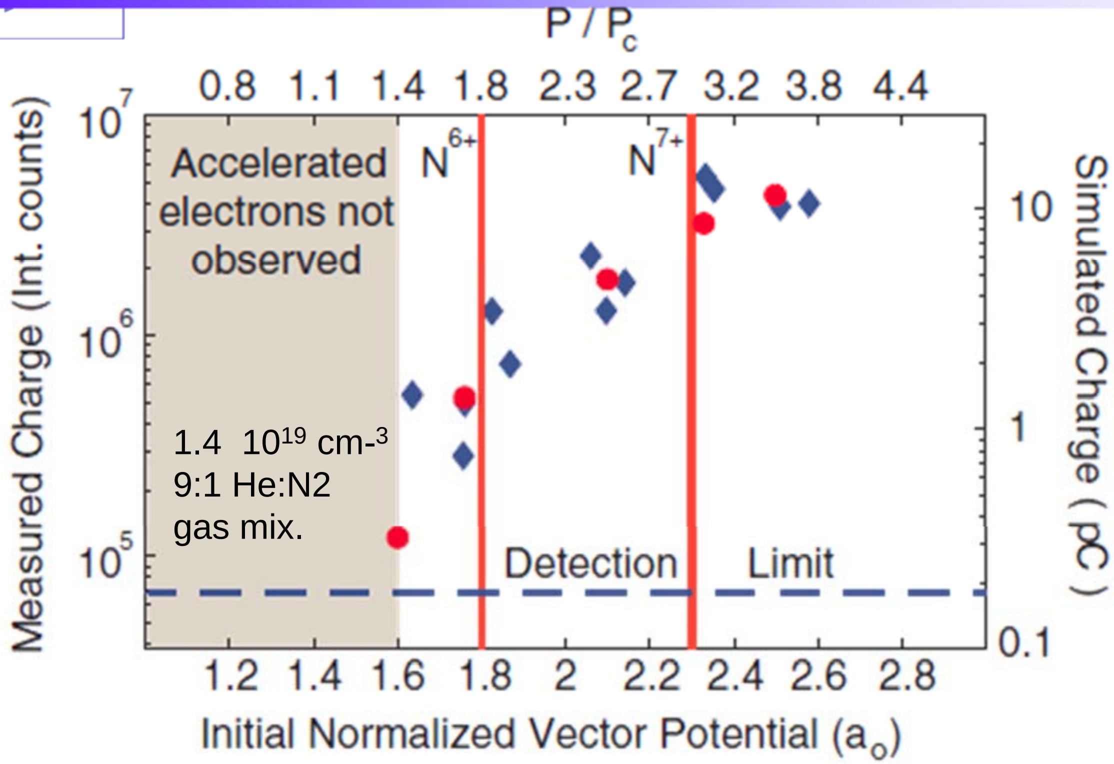


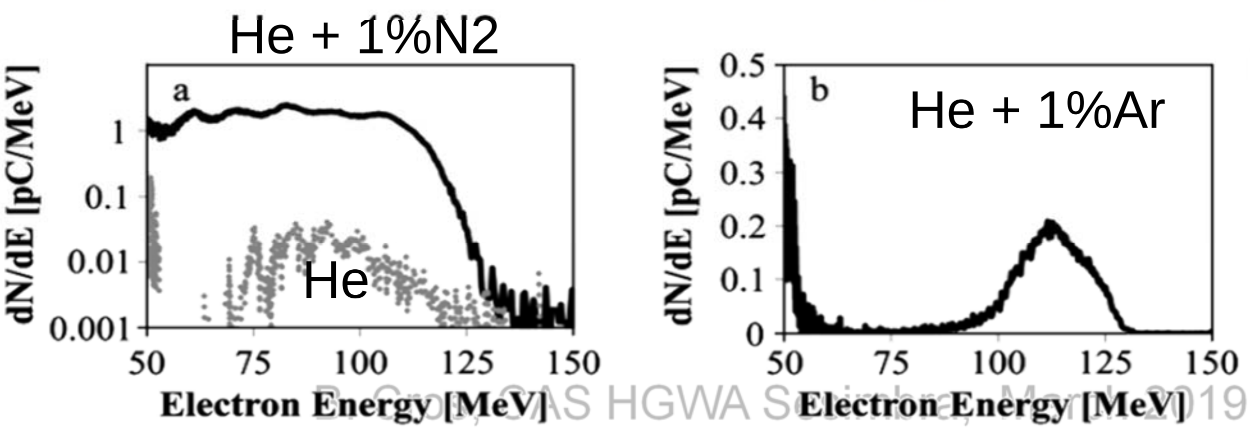
A. Pak *et al.*, PRL – **104**, 025003 (2010)

An electron born close to the peak of the laser envelope will be trapped



Main characteristics of ionisation assisted injection





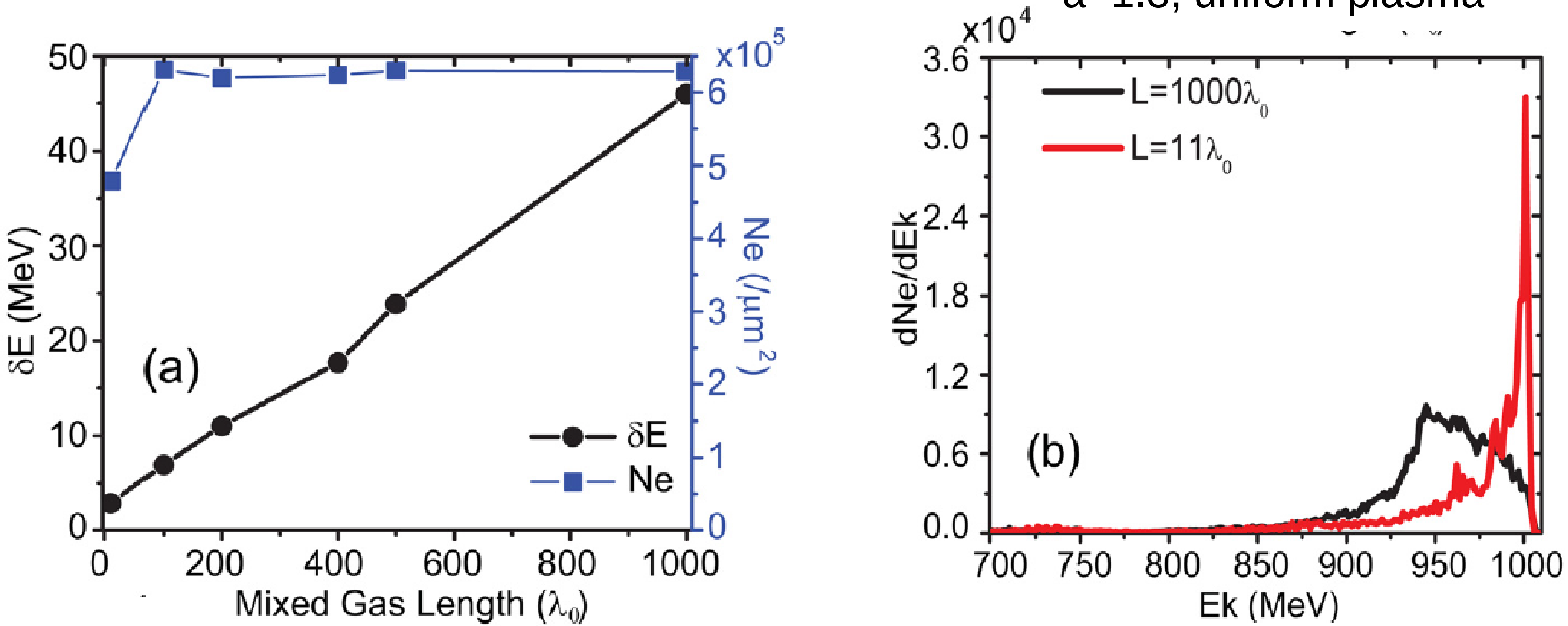
Example of spectra

- Lowers injection threshold compared to self-injection (from Pak et al.)
- Large accelerated charge (from Mc Guffey et al)
- Wide electron spectra when injection occurs over a large distance

Injection length needs to be optimized for the design energy

Energy spread grows with gas length

a=1.8, uniform plasma



- Simulations from Chen Phys. Plasmas 19, 033101 (2012)

Outline

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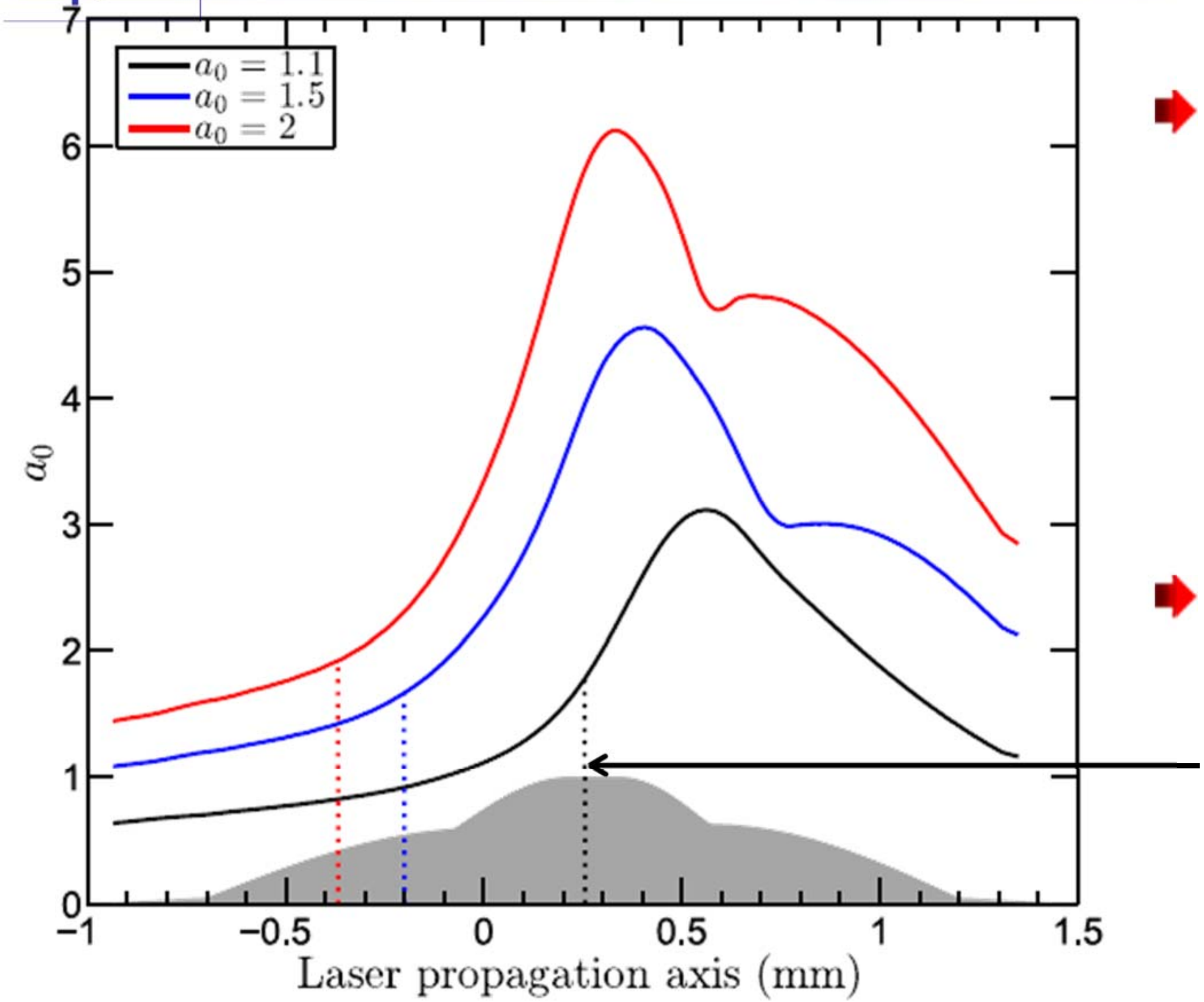
IAI combined to density tayloring to improve beam properties

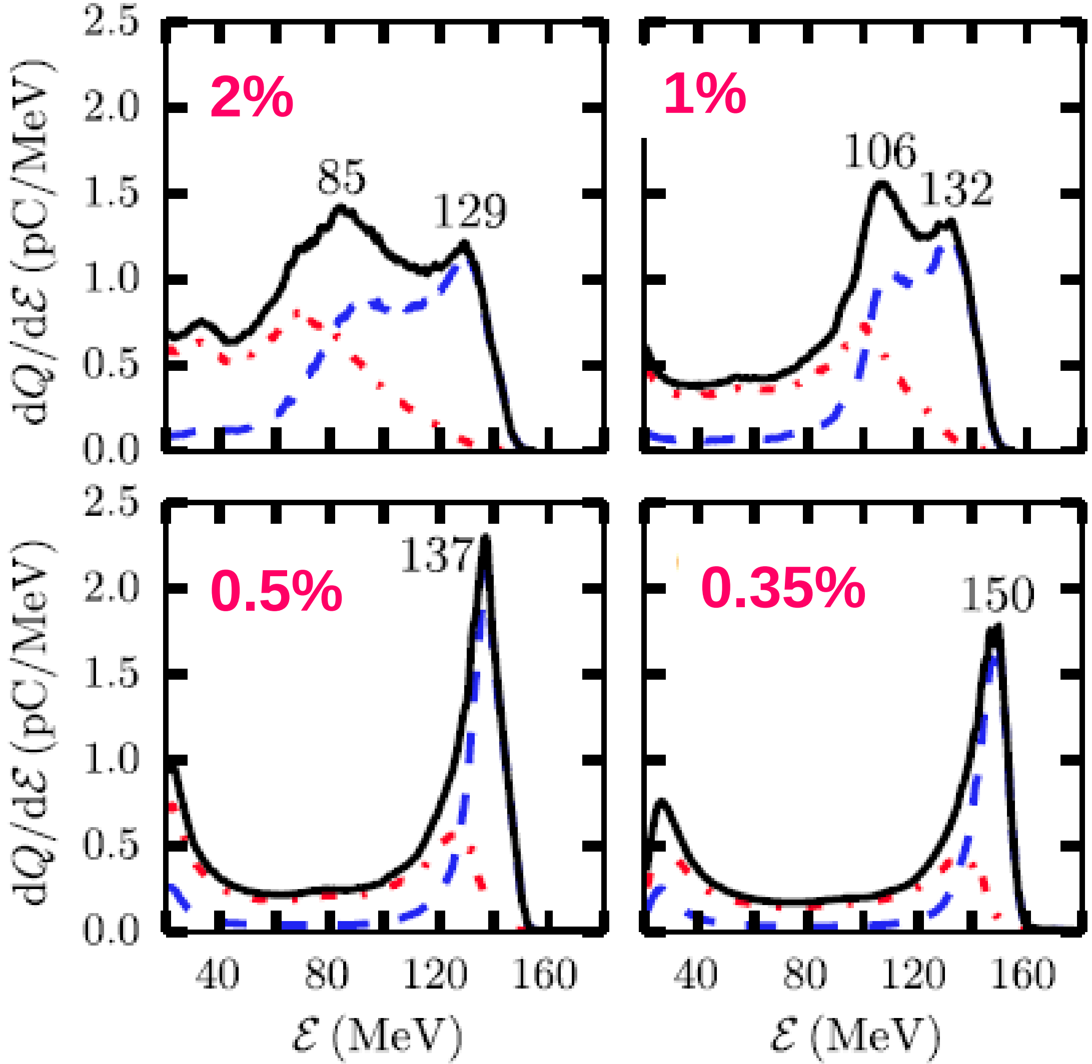


- Electron spectra are controlled by the laser focus position relatively to the plasma profile
- Pulse evolution in the plasma determines the position where injection starts (vertical lines)

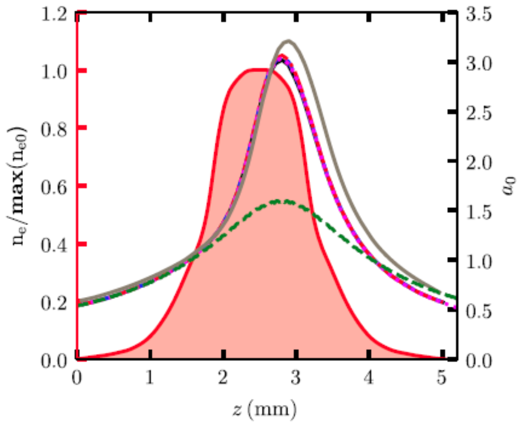
Audet et al, Phys. Plasmas 23, 023110 (2016)

Species concentration as a parameter to control spectra

a0 max in vacuum = 1.6

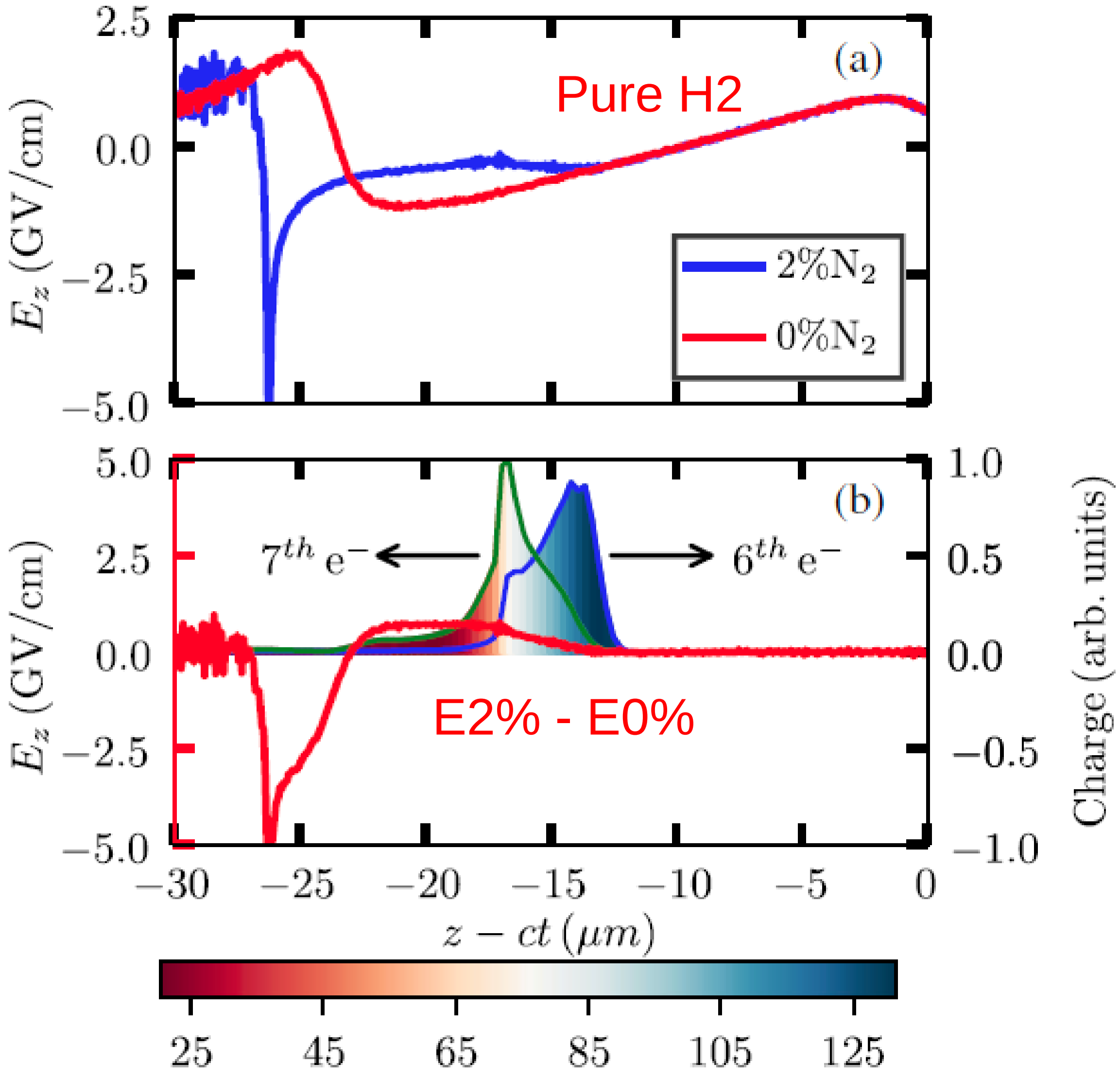


- Helps to tune electron energy and reduce energy spread through the control of beam loading



Lee et al, PRAB 21, 052802 (2018)

Detailed analysis highlights the role of beam loading

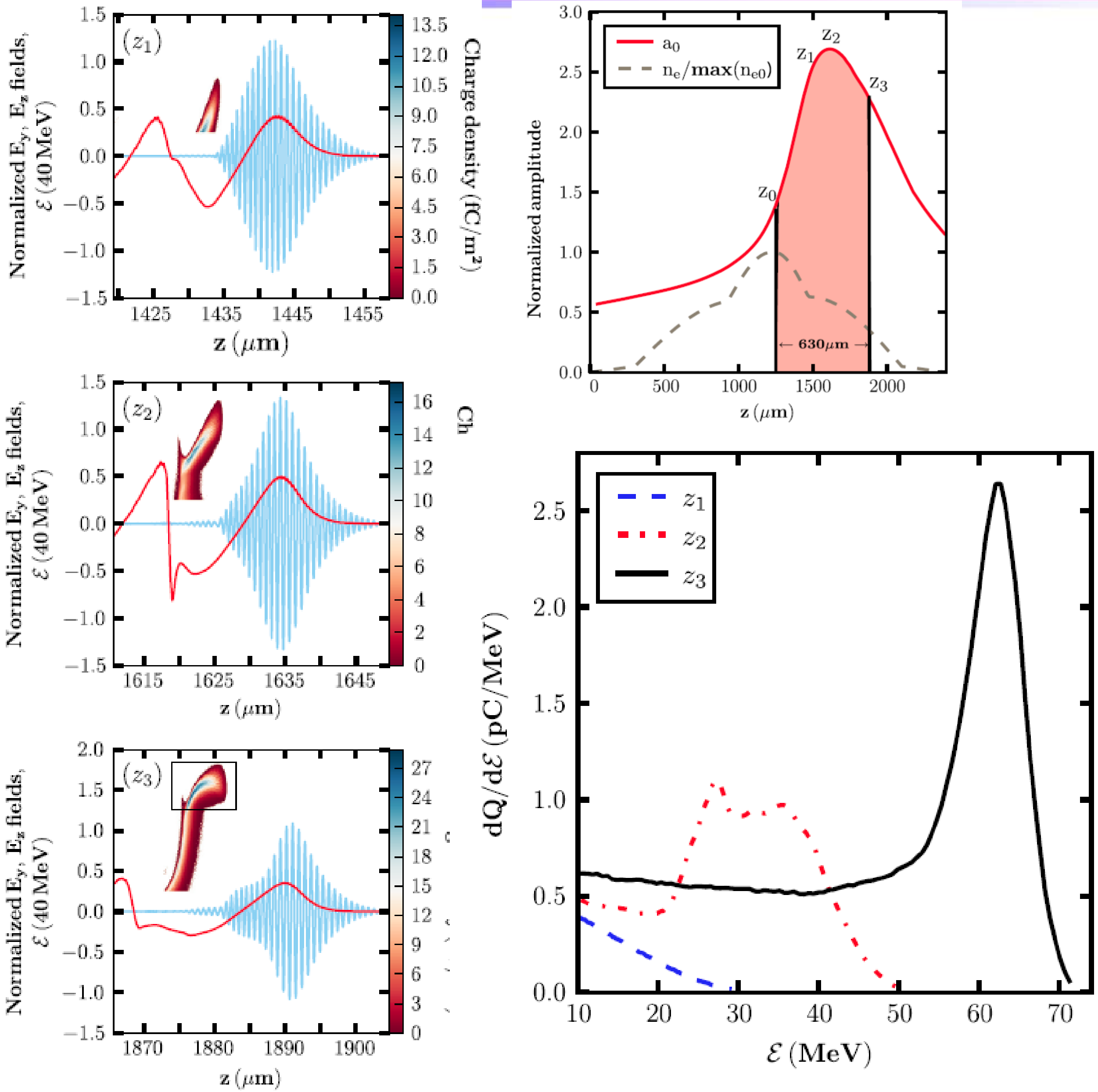


Electron energy $\langle \mathcal{E} \rangle$ (MeV)

- IAI favors large charge bunches leading to significant additional wakefield (beam loading)
- Changes the accelerating field
- Energy spread linked to ionisation

Lee et al, PRAB 21, 052802 (2018)

Beam loading combined to short injection zone at moderate laser power

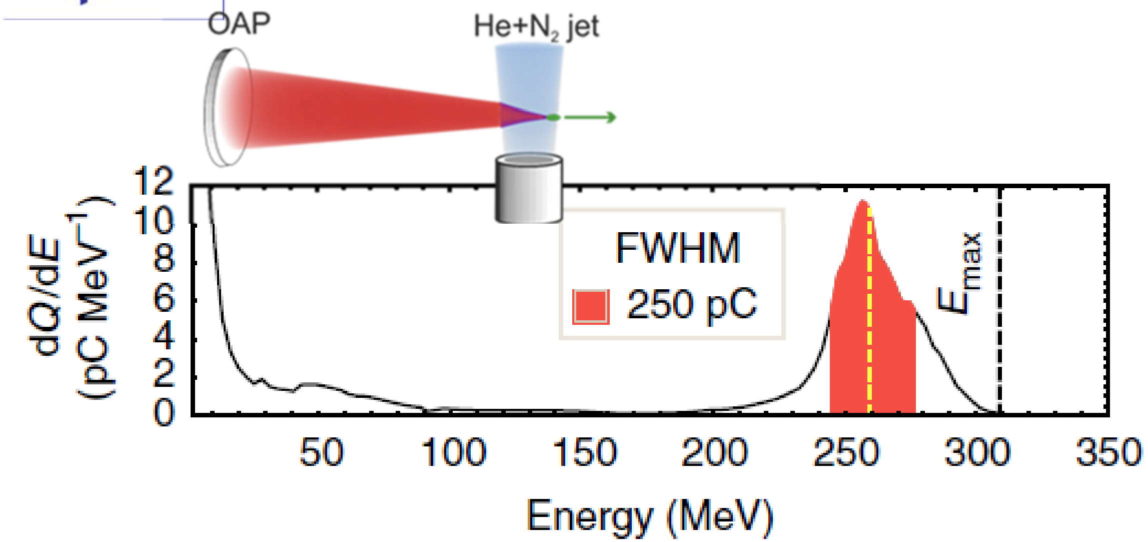


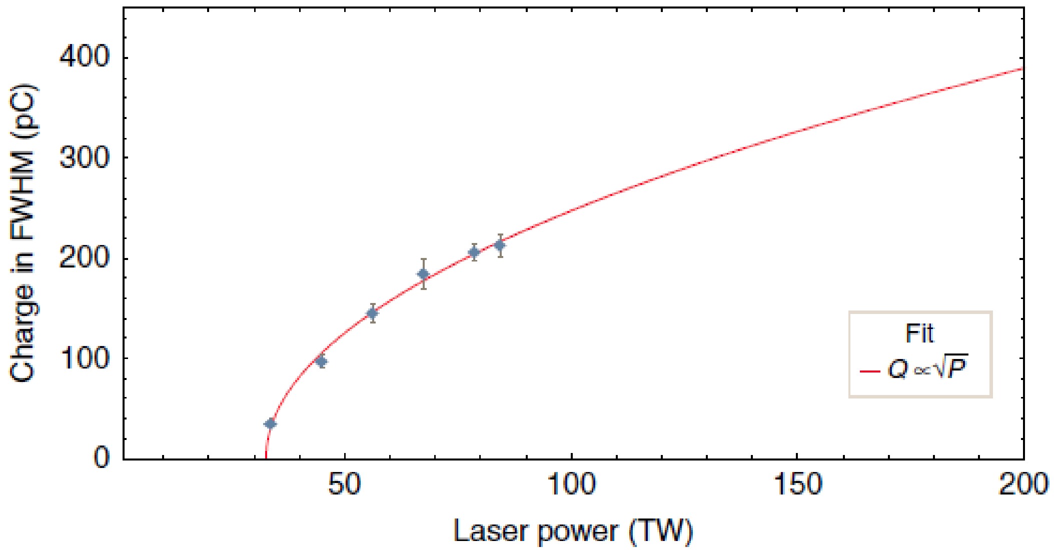
Injection zone of length 630µm

Moderate laser power
Slow growth of laser amplitude $a_0 = 1.1$, focused at Z_3

Energy ~60 MeV
Energy spread FWHM ~10%

Combination of IAI and profile tailoring at large laser power

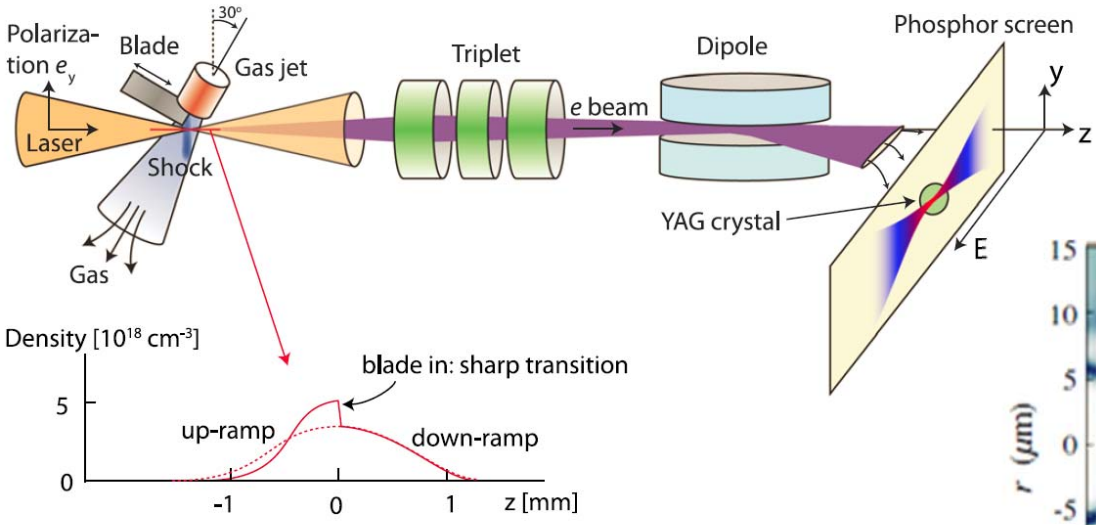




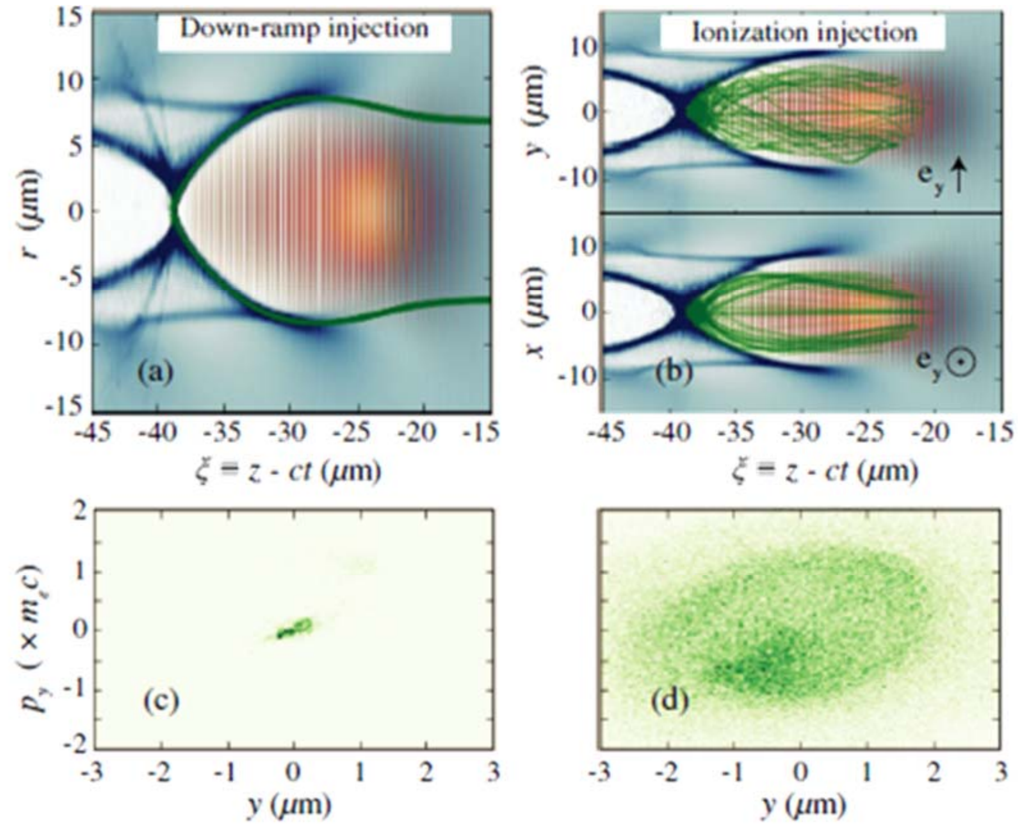
- He+ N_2 1%, plasma density $3.1x10^{18}cm^{-3}$
- Focused at the back of a gas jet
- Energy spread FWHM 15%
- Benefits from optimized condition for beam loading , ~0.5nC for 200TW laser power

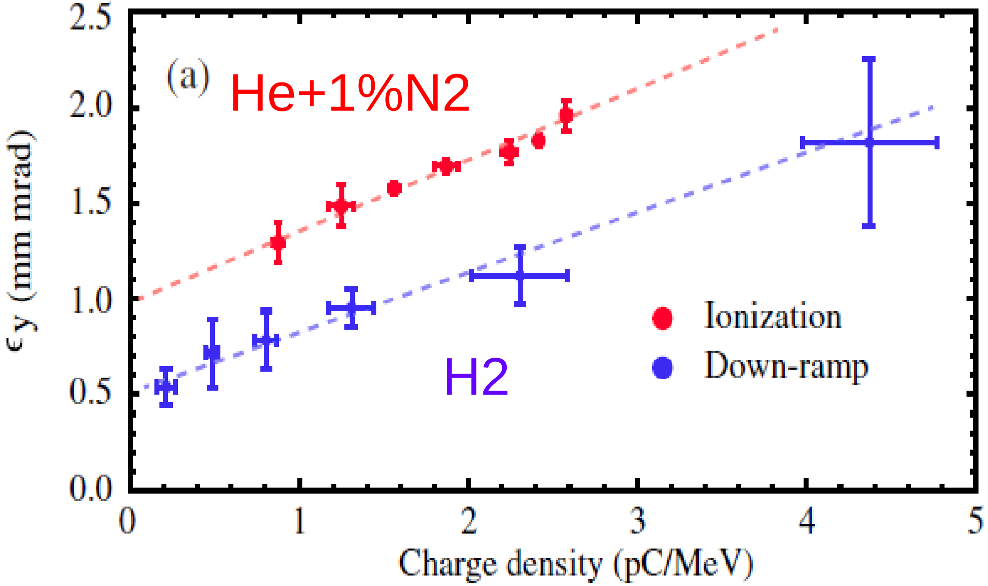
Couperus Nature comm 8,487 (2017)

Emittance is determined by the injection process



Comparison of downramp and ionization injection





55-62 MeV range

Barber et al, PRL 119, 104801 (2017)

Achieved parameters for electron sources at plasma exit

Beam parameters	Range
Energy	50-300 MeV------>>1 GeV
Charge	0.1-30 pC--------->>100 pC
Bunch length	3-20 fs
Repetition rate	< 1 Hz
Energy spread	1 -15% ------------->>50%
Transverse normalized Emittance	1 -5 mmmrad
Transverse size	3-10 µm
Transverse divergence	1-10 mrad

Driven by 20TW to 500TW laser power

- High charge 100 pC combined with low energy spread (5%rms) and low emittance (1mm mrad) are essential and still need to be demonstrated

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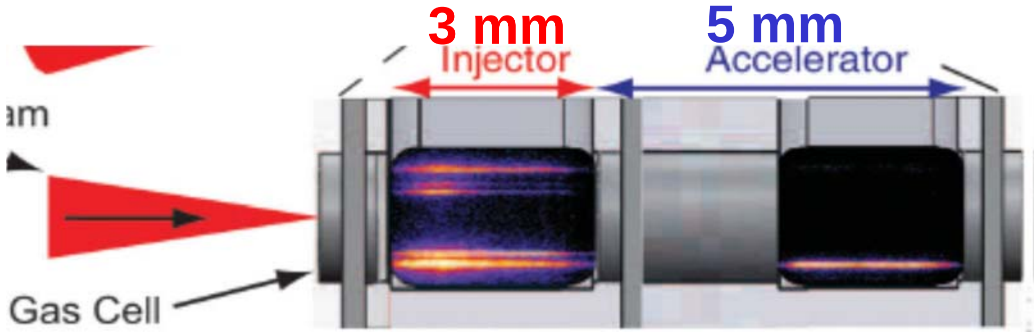
Attempts to use these sources as injectors

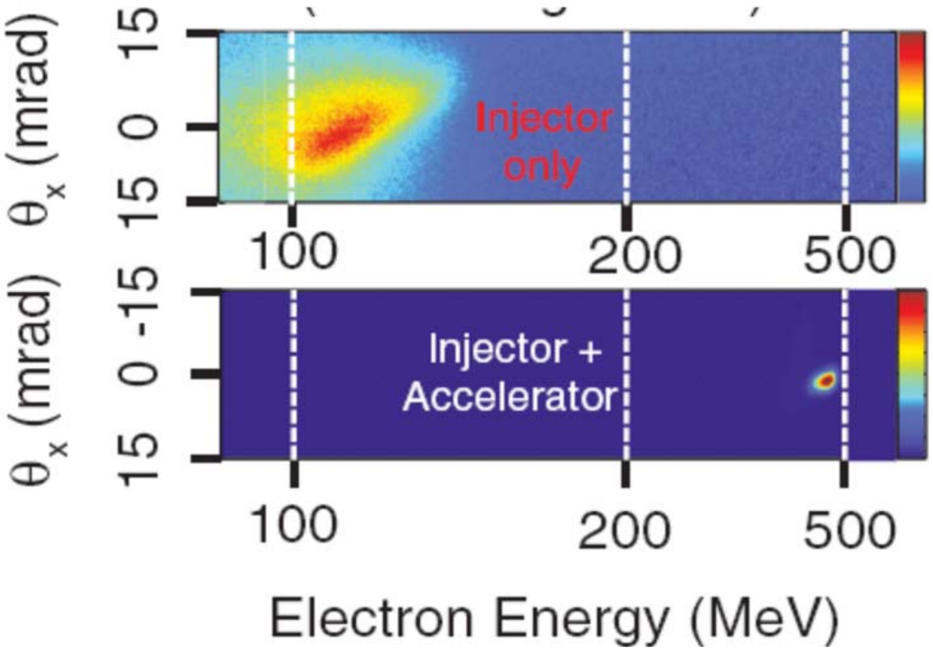
- **Schemes with 1 laser beam**:
  - Tailored density profile with long tail: injection zone followed by acceleration zone, both driven by the same laser pulse
  - With or without assistance from ionisation
- **Scheme with 2 or more laser beams >** multi-stage
  - At least 2 laser pulses driving 2 plasma stages
  - improved accelerating section but new issues arise due to beam/plasma coupling between stages

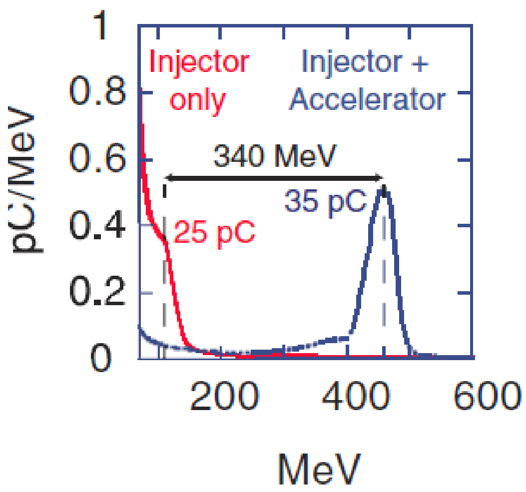
Examples >>>

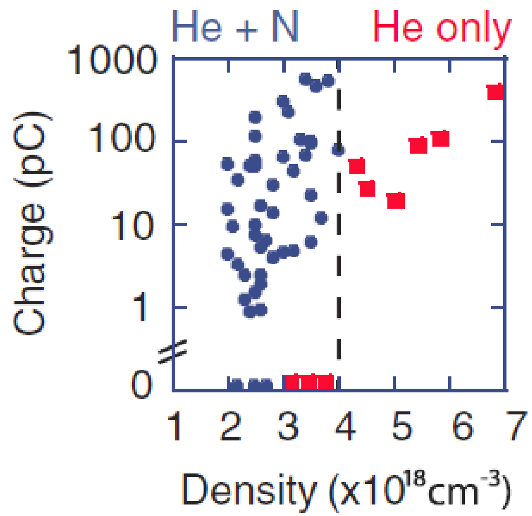
First test of ionisation injection followed by accelerator tail



- Laser 40TW, $n_e=3\times10^{18}cm^{-3}$
- 0.5% Nitrogen in the injector:
- Lower density accelerator He:
  Means longer dephasing length
  ie longer acceleration length



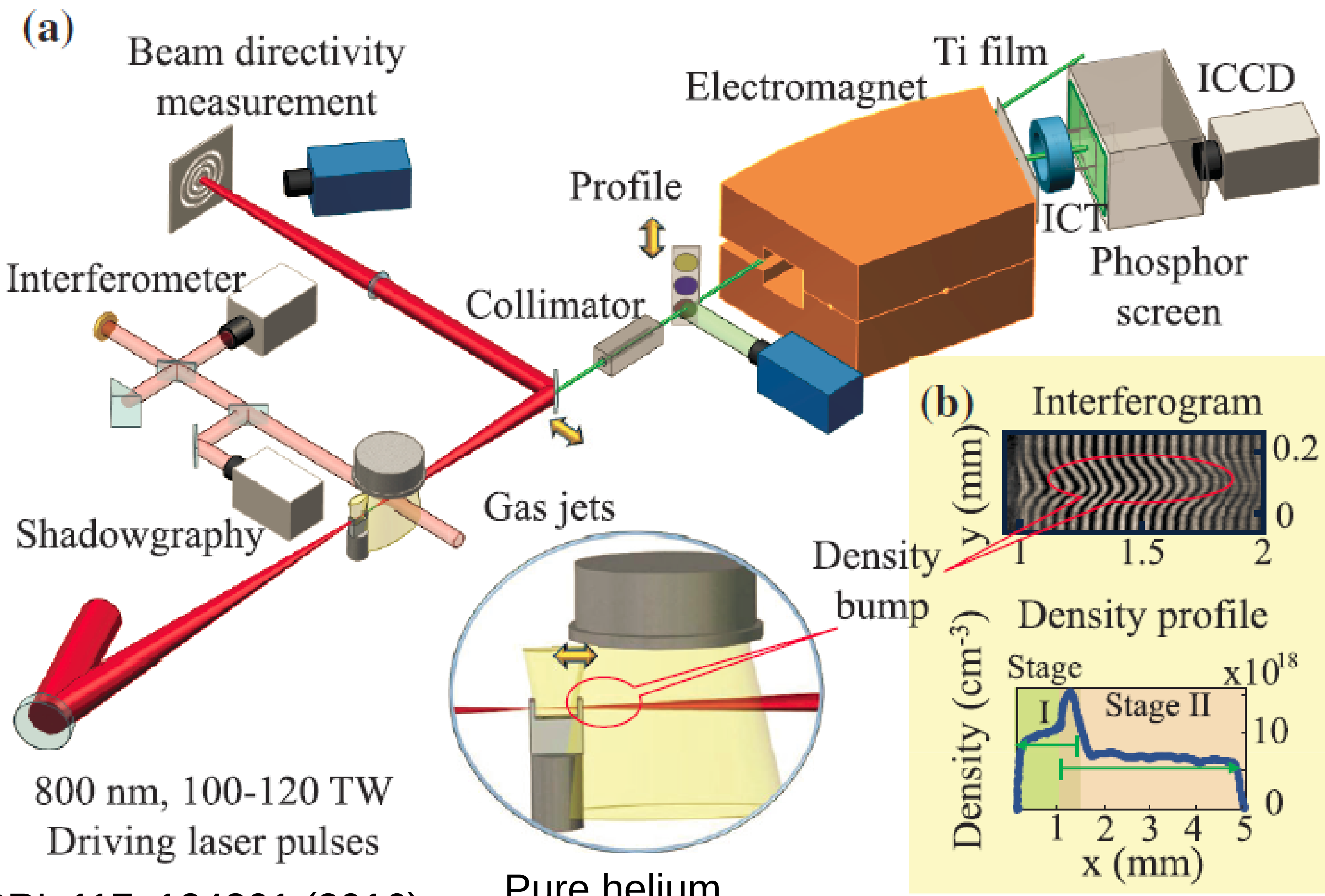




1.4pC/MeV, Energy Spread FWHM 5%
2.3 mrad divergence

Pollock et al., Phys Rev. Lett 2011 (LLNL)

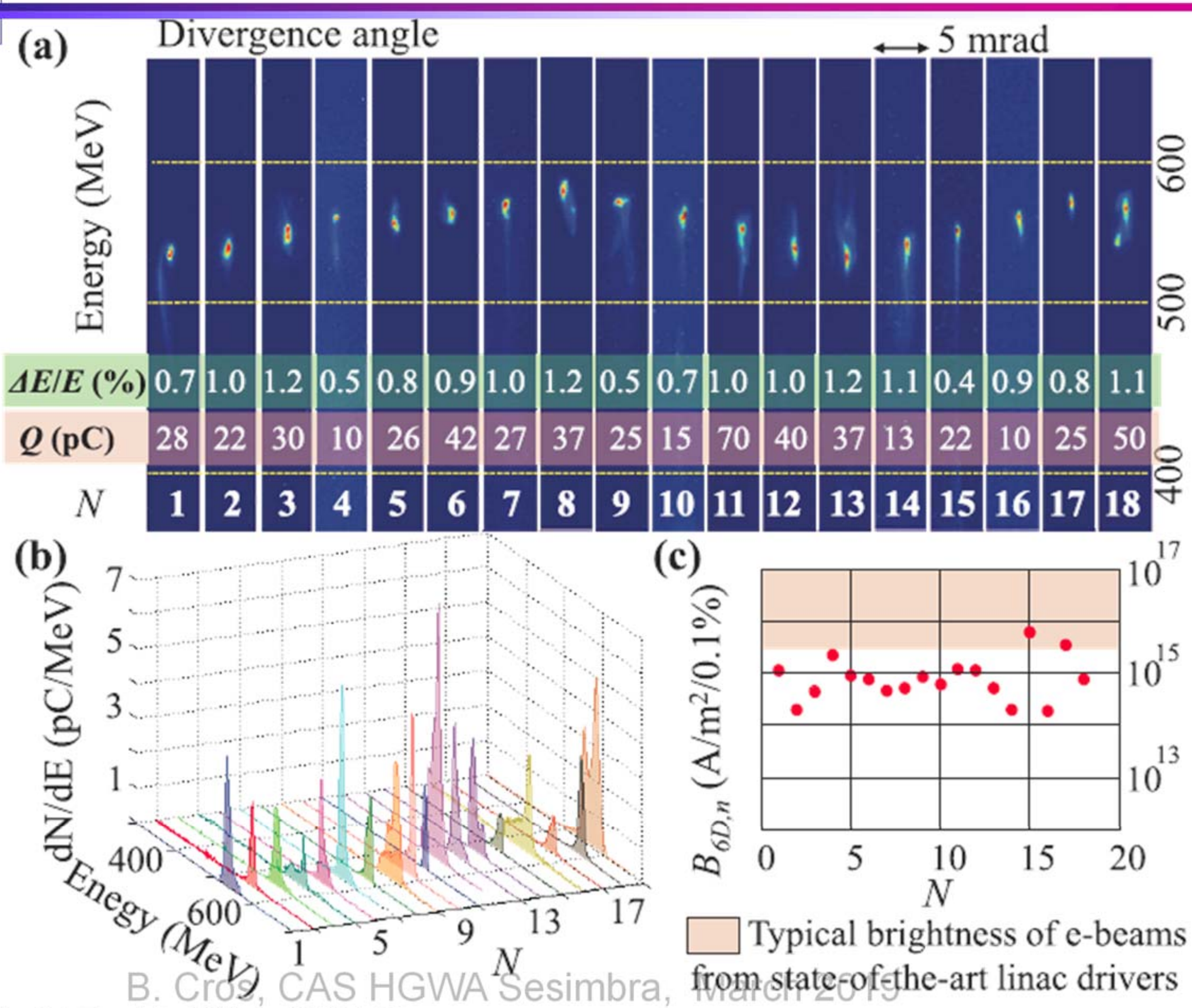
Double gas jet to tailor plasma density in pure He



Pure helium

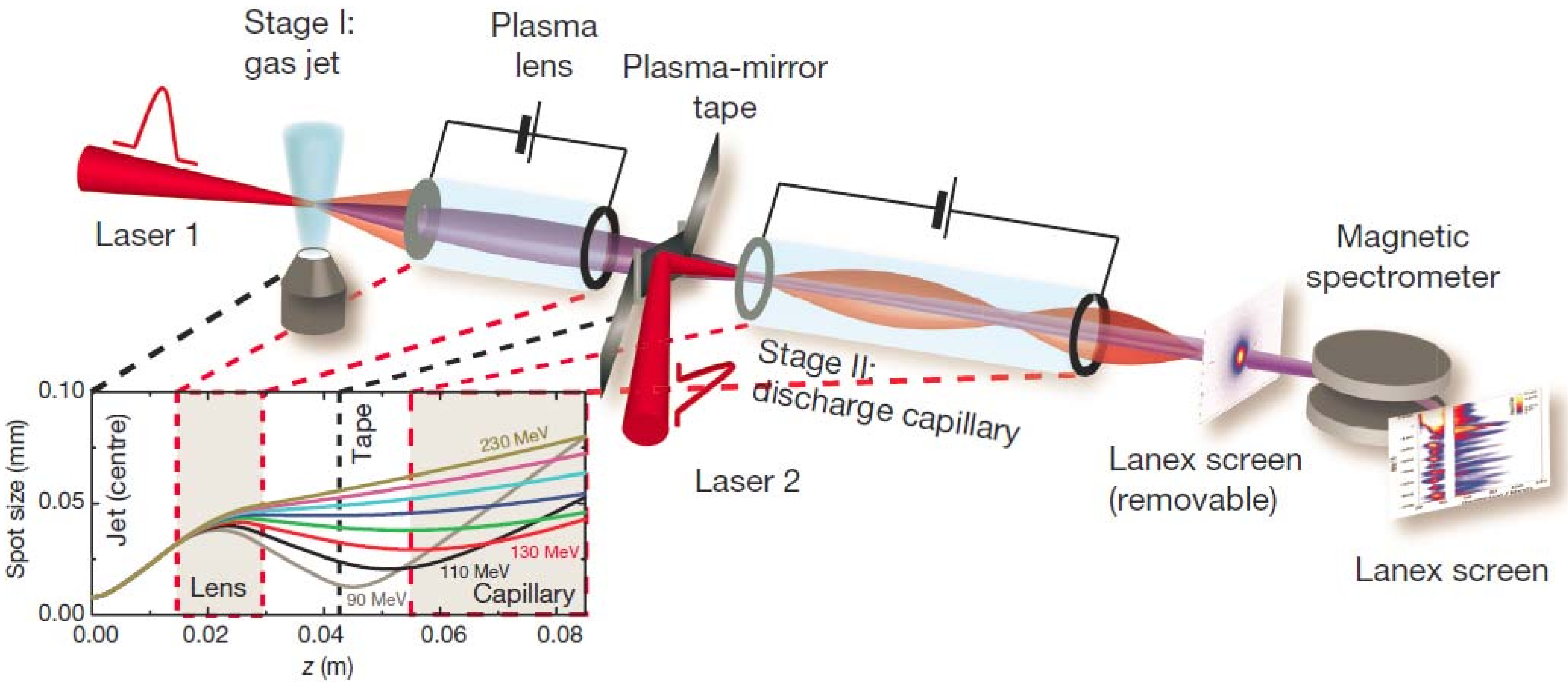
Wang PRL 117, 124801 (2016)

Increased charge measured: 1-5 pC/MeV around 550 MeV



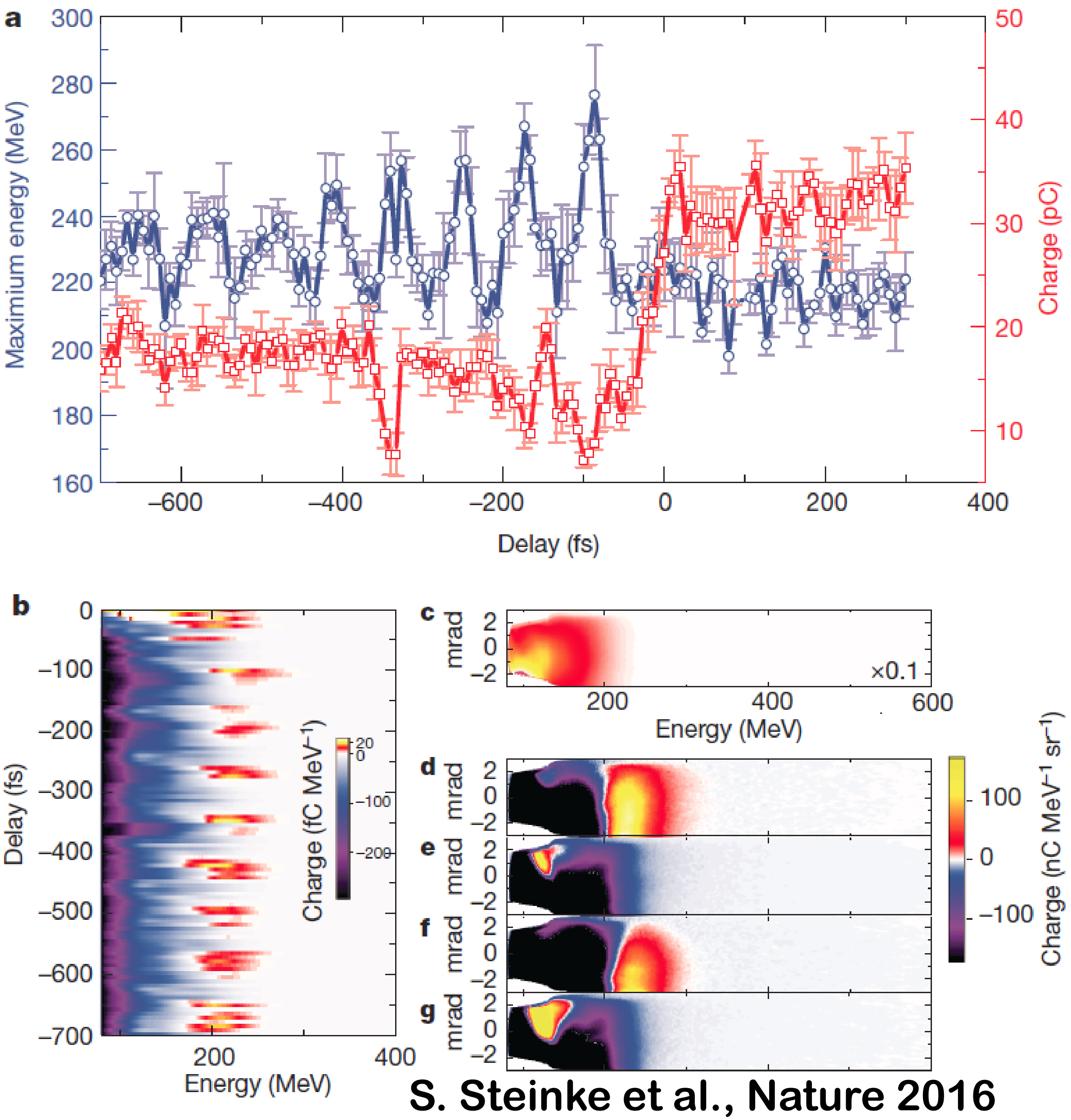
Wang PRL 117, 124801 (2016)

Coupling an electron source to a plasma accelerator



S. Steinke et al., Nature 2016

Electrons injected at varying delays experience different phases



S. Steinke et al., Nature 2016

- Maximum energy gain depends on delay between laser pulses
- Entrance bunch (reference)
- Spectra at exit of second stage (reference substracted)

Summary

- Laser driven wakefield in plasmas can generate **electron sources** in a range of parameters suitable for an electron injector (50-500 MeV, 1-10 pC/MeV, divergence 1mm mrad)
- **Several concepts and techniques** are being studied to optimise electron parameters according to the requirements for transport and applications; f**ast progress** has been achieved over the last 10 years
- **Controlled injection** into a plasma wave accelerator will open the way to accelerator development

References for electron trapping and acceleration

- Esarey et al, Phys Plasmas, 2 1436 (1995)
- Mora et al, J Apl Phys **66**, 3476 (1989)
- Mora, Phys Fluids B **4**, 1630 (1992)

References for colliding pulse injection

J. Faure *et al.*, Nature (2006)

C. Rechatin *et al.*, PRL (2009)

Faure, proceedings of CAS 2014

Geddes et al. AIP Conference Proceedings, 1777(1):040003, 2016.

Cormier-Michel, PRAB, 17, 091301 (2014)

Selected references on shock injection

- Schmid et al, PRAB, 13, 091301 (2010)
- Buck et al, PRL 110, 185006 (2013)
- Burza et al, PRAB 16, 011301 (2013)
- Hansson et al, 18, 071303 (2015)

- smooth density down ramp ($L_s \gg k_p^{-1}$) [89];
- sharp downward density transition ($L_s < k_p^{-1}$)[90].

Selected references on ionisation assisted injection

- Clayton, PRL 105, 105003 (2010)
- McGuffey et al.PRL 104, 025004 (2010)
- Pak PRL 104, 025003 (2010),
- Chen et al., Phys. Plasmas 19, 033101 (2012)
- Audet et al, Phys. Plasmas 23, 023110 (2016)
- Lee et al, PRAB 21, 052802 (2018)
- Couperus et al , Nature comm 8,487 (2017)