Optimisation of the laser-plasma injector via space charge effects using ionisation-induced injection

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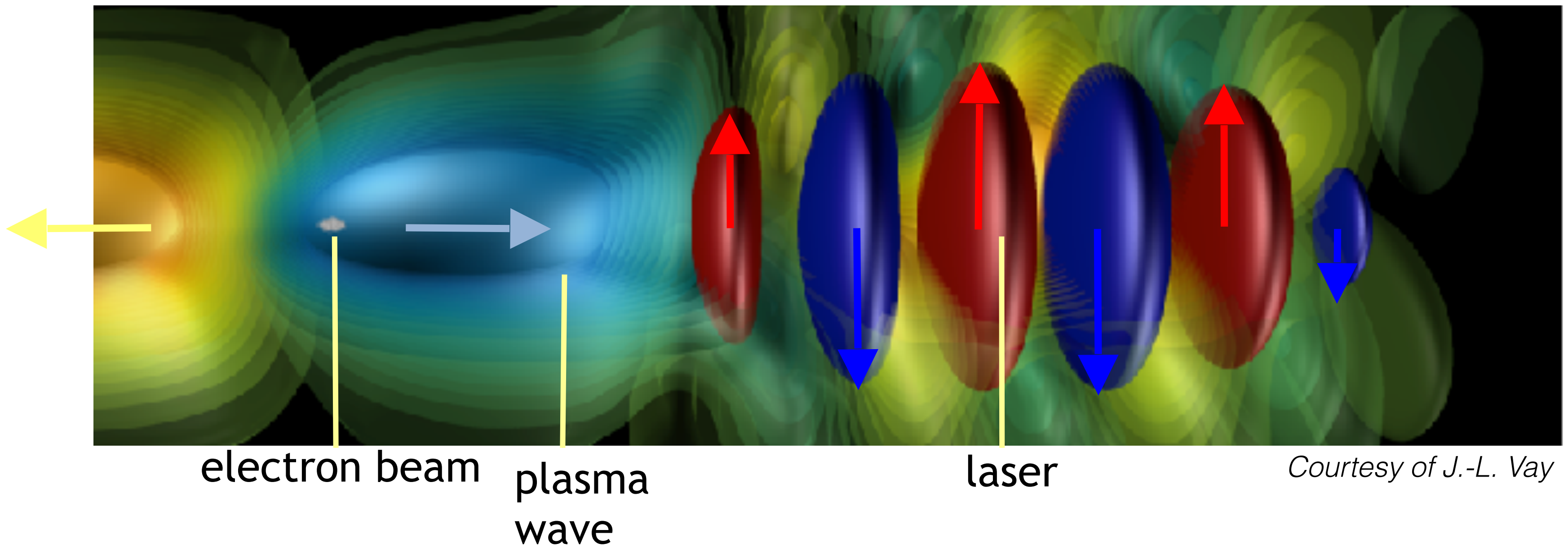
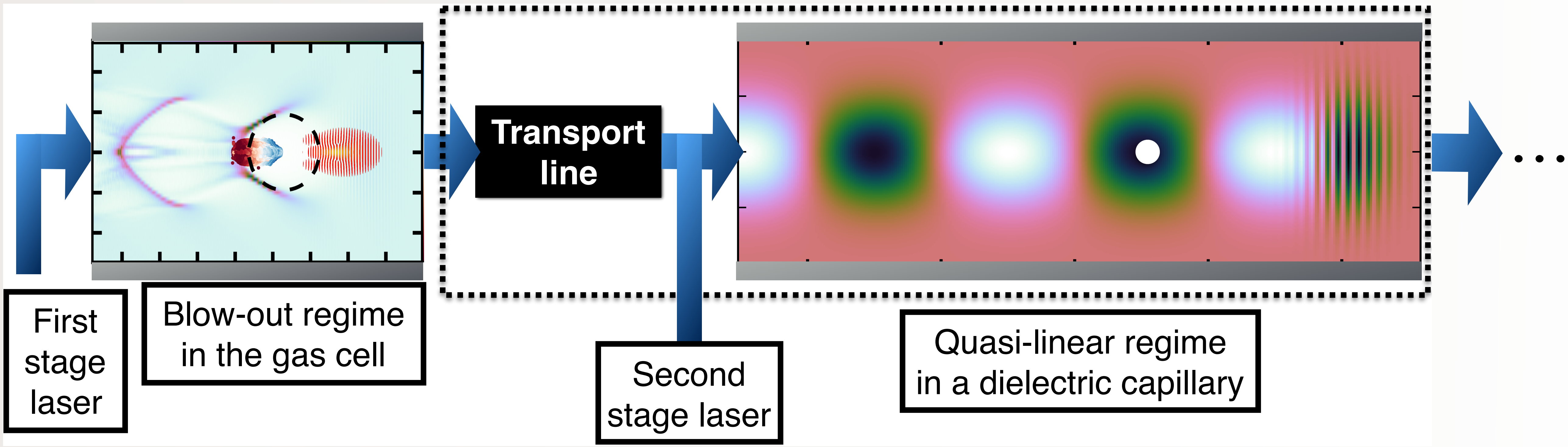
Advantages and limitations of Laser Wakefield Accelerator



Accelerating gradient	$E_z \gtrsim 100$GV/m (1mm=>100MeV)
Electron beam length	~μm
Limitations	laser depletion laser diffraction electron dephasing

multi-stage accelerator

High energy electron acceleration in a two-stage accelerator



- **an injector** : a few mm long dense plasma, complex physics, highly nonlinear, intrinsically 3D
- **a transport line**: a few m long
- **an accelerator** : a few m long less dense plasma

Ionisation injection scheme for the injector

Electron beam specifications for the injector (CILEX, EuPRAXIA):

- energy range between 50-200 MeV
- narrow energy spread ($\Delta\mathcal{E}_{rms}/\left\langle\mathcal{E}\right\rangle \lesssim$5%)
- high charge ($Q \gtrsim$10 pC)
- rms transverse divergence ($\theta \lesssim$5mrad)
- rms normalised emittance ($\varepsilon \lesssim$1mm.mrad)

Existing injection schemes

- self-injection scheme
- density gradient based injection scheme
- multiple lasers injection scheme
- ionisation injection scheme
- mixed techniques

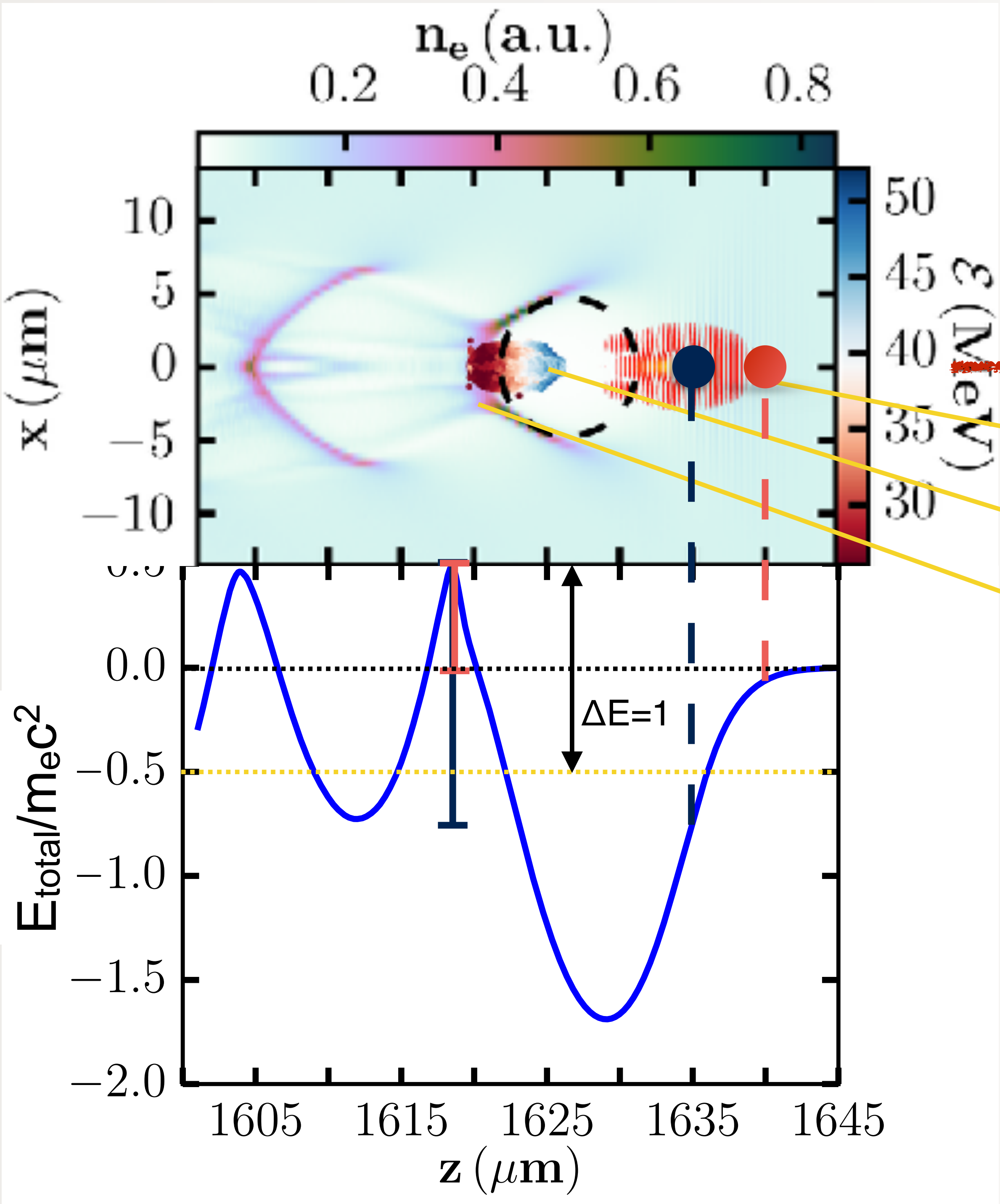
T. L. Audet, WG4 Thursday,18:00

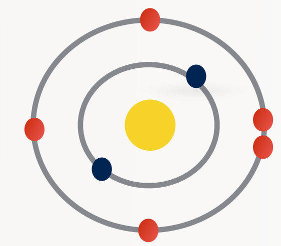
Why ionisation injection scheme?

- generate high charge electron beam
- shot-to-shot stability
- simple experimental setup
- additional control parameter

Ionisation injection scheme: the basics

Electron density

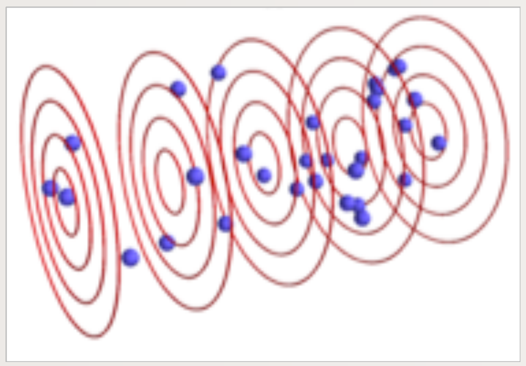




*Warp is well adapted to model laser-plasma injector

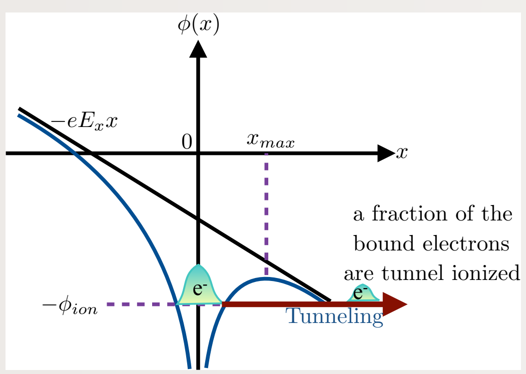
Warp : open source PIC code, co-developed at LBNL

J.-L Vay et al. Computational Science & Discovery, 2012

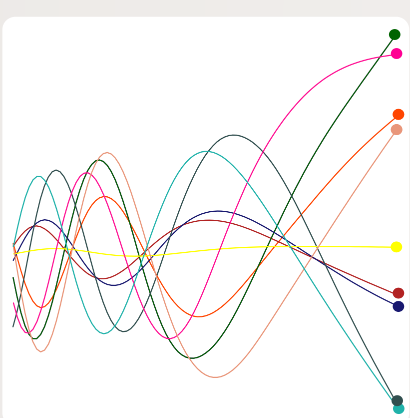


Quasi 3D: angular Fourier decomposition algorithm†

$\Delta z = [\lambda_0/30, \lambda_0/25]$, $\Delta r = \lambda_0/6$, # macroparticles/cell/species = 36, Fourier modes = [-1,0,+1]



Ionisation processes: Ionisation module using the ADK model

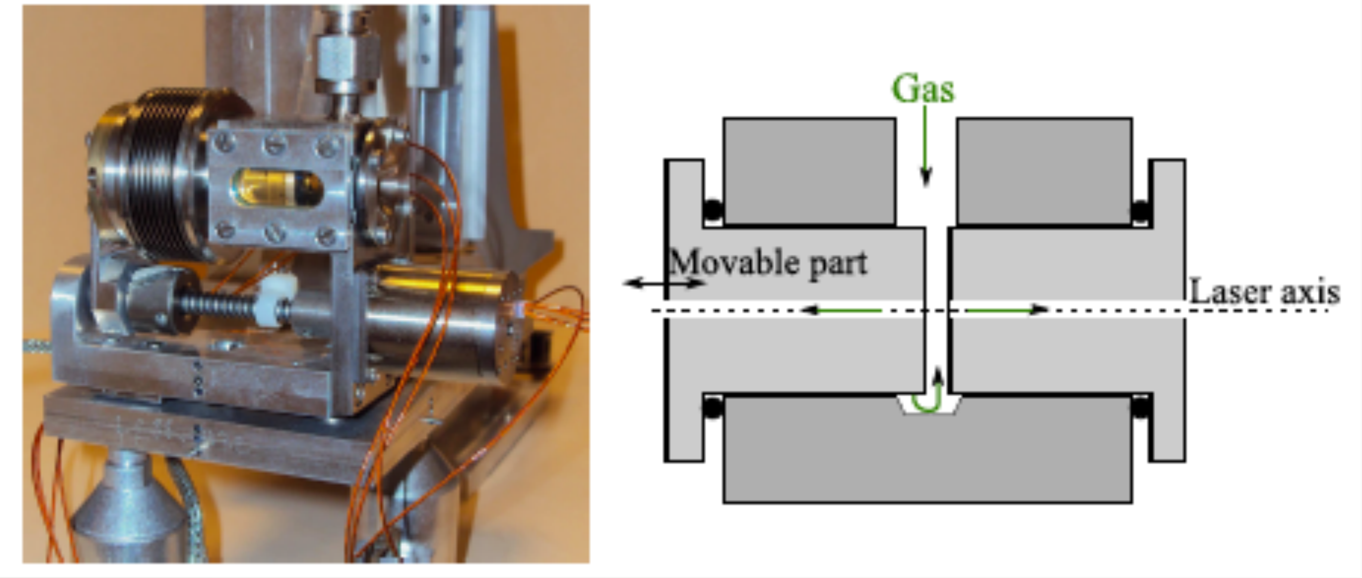


Trajectory analysis: particle tracking module

*J.-L Vay et al. Computational Science & Discovery, 2012

†A. F. Lifschitz et al. JCP, 2009

Plasma target : ELISA†



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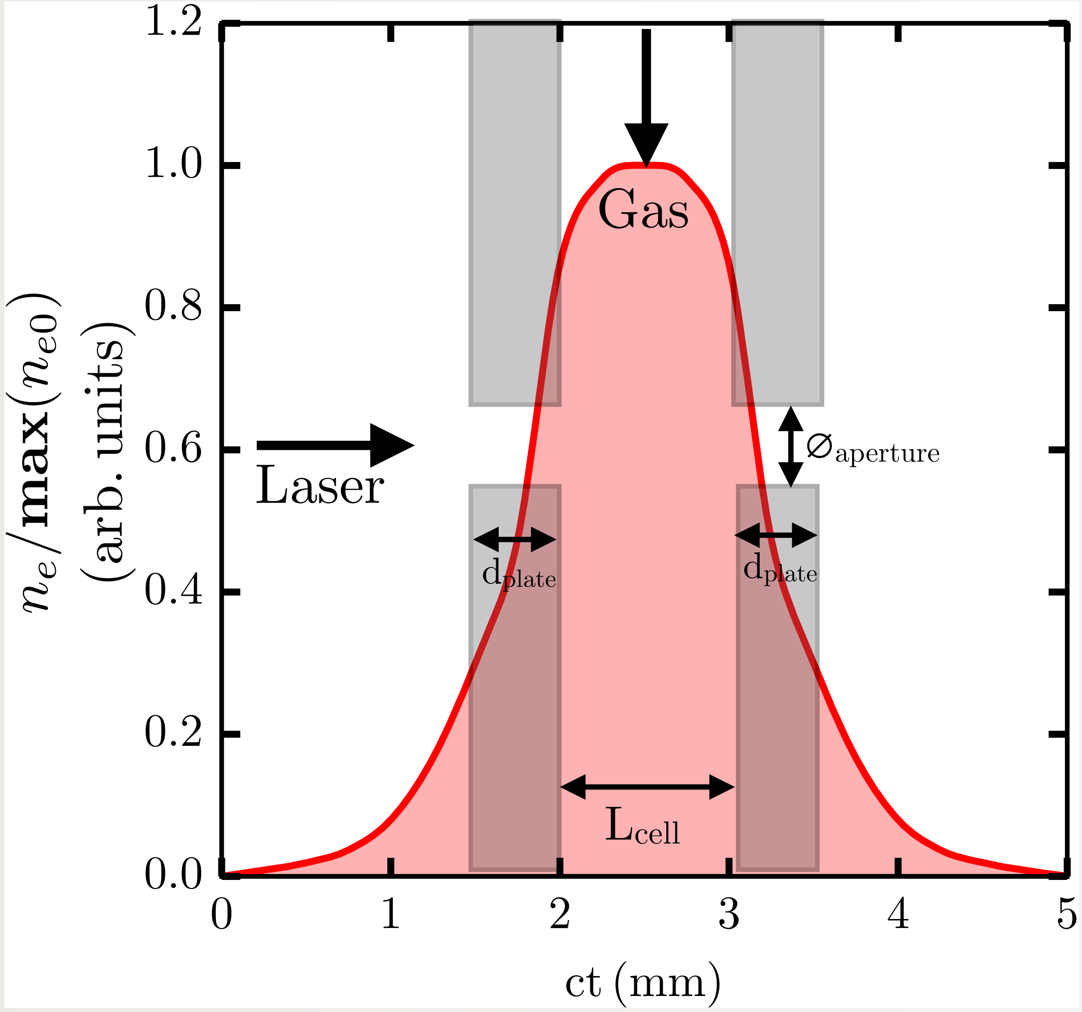
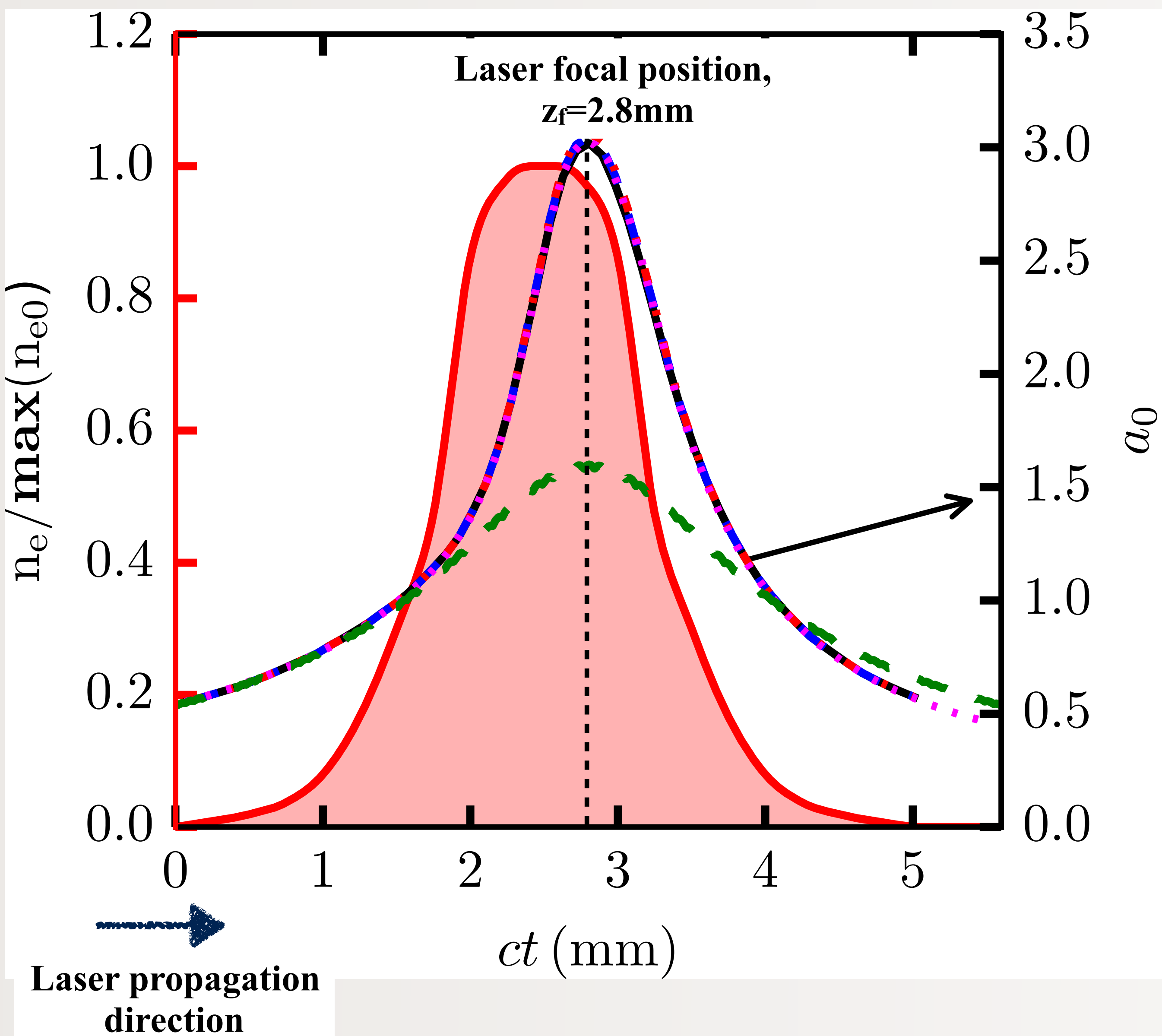


- ELISA longitudinal density profile well characterised experimentally and by fluid dynamics simulations
- L_{cell} = 1.0 mm
- $\varnothing_{aperture}$ = 600 μm
- d_{plate} (entry and exit) =500 μm

†Electron injector for compact staged high energy accelerator
*T.-L. Audet et al. NIM-A, 2016

Varying nitrogen concentration to control space charge effects

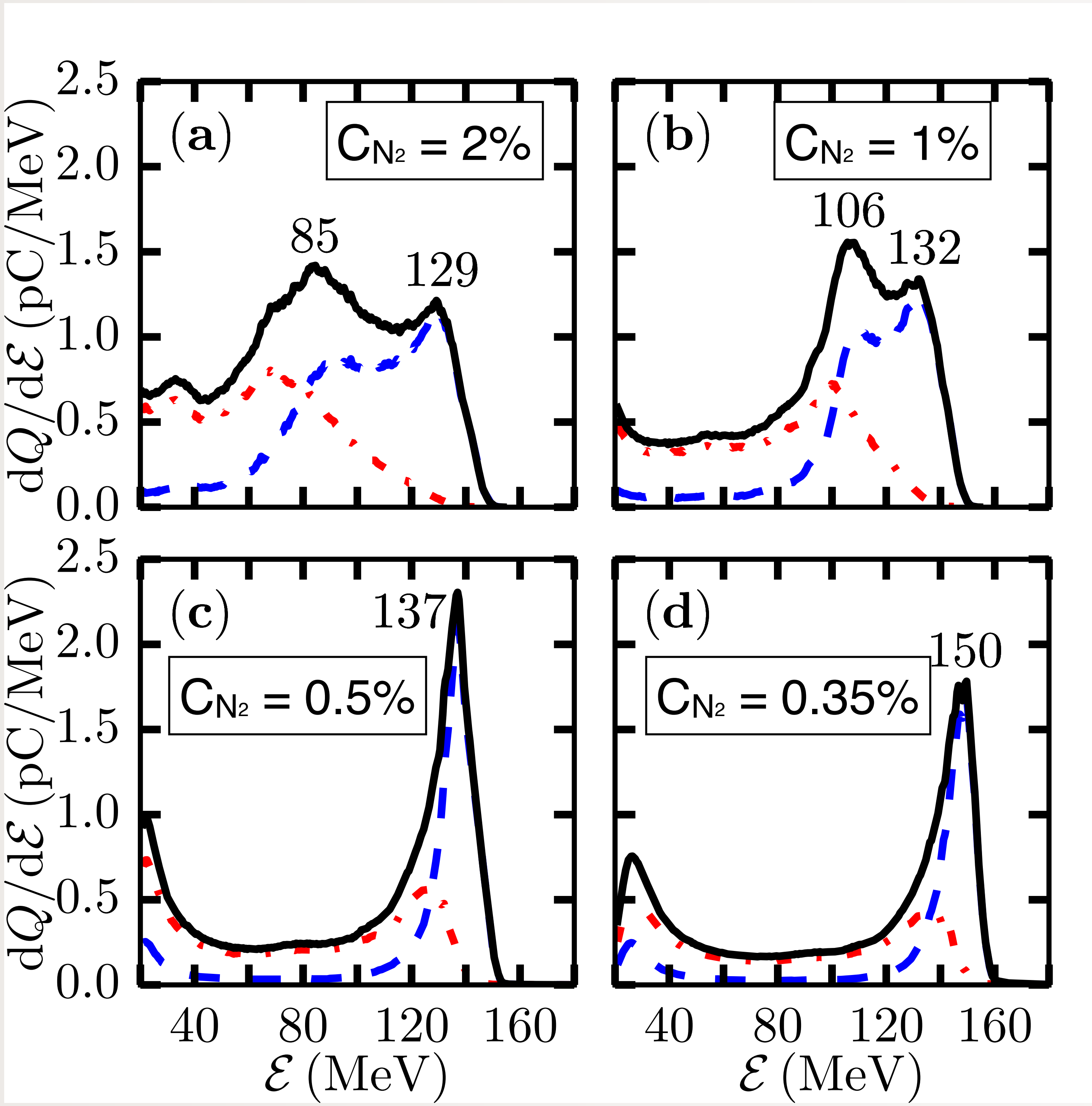
*Choice of parameters:
- nitrogen concentration, C_{N_2}= [0, 0.35, 0.5, 1.0, 2.0]%
- maximum electron number density, $\max(n_{e0}) = 4.\times10^{18}\ cm^{-3}$
- laser parameters: 100 TW, 20 fs FWHM, w_L = 16 μm
- moderate Gaussian power laser pulse, initial potential vector, a_0 =1.6

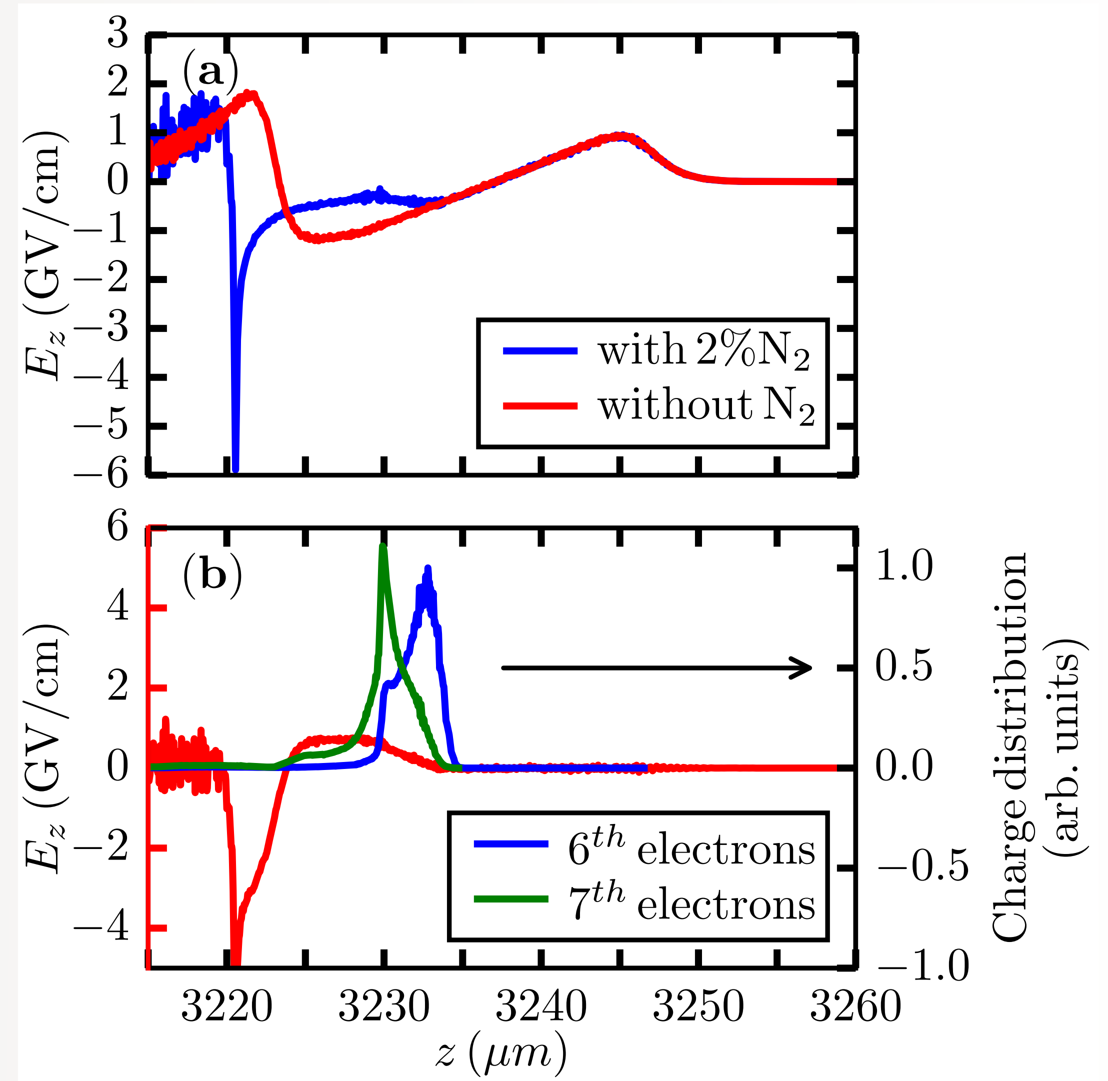


- evolution of a_0 independent of C_{N_2}
  →generated plasma wave similar in all cases
  →study narrows down to only space-charge effects

*P. Lee et al. PRAB, 2016.

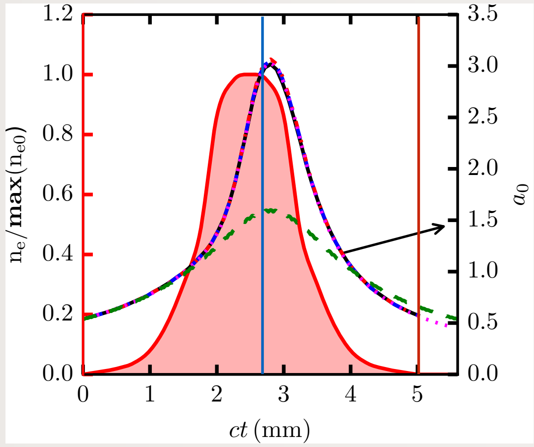
Space charge effects are responsible for the energy distribution of the accelerated electrons



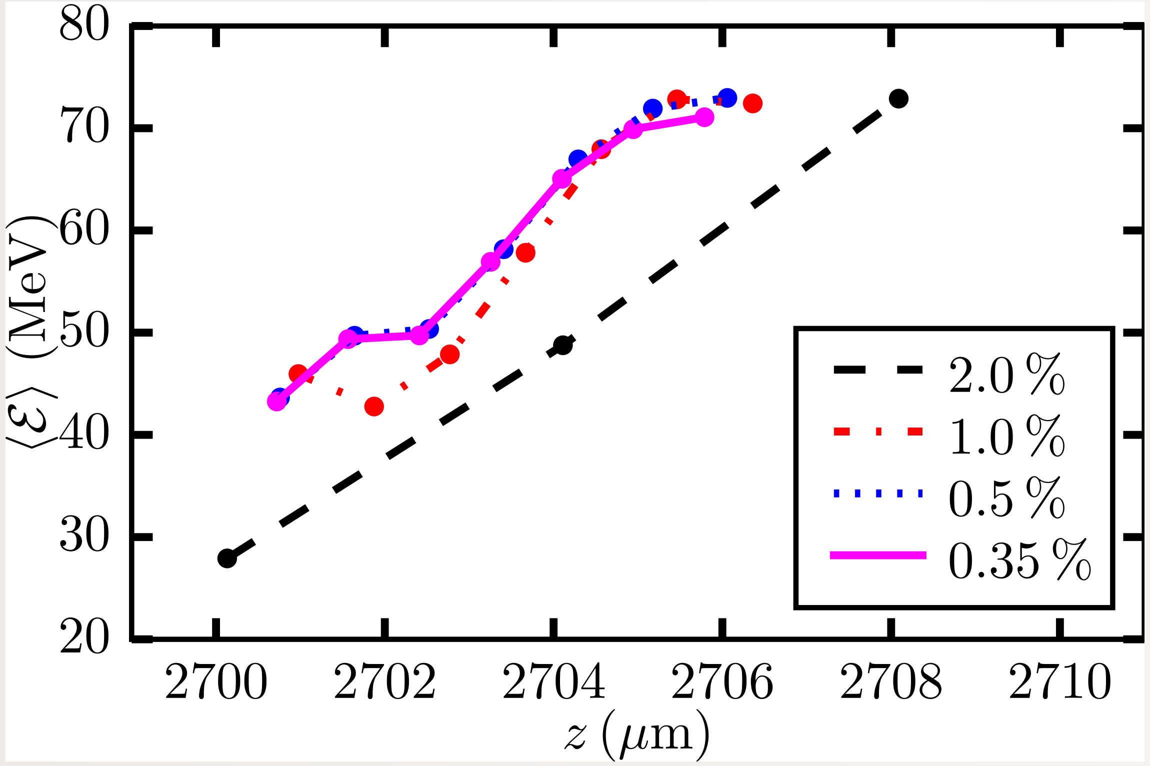


- formation of 2 peaks for C$_{N_2}$ ≥ 1%
- induced space charge field flattens the accelerating field
- low energy electrons at the back of the bunch never catch up with the high energy electrons

Space charge effects correlate with the degree of phase space rotation of accelerated electrons

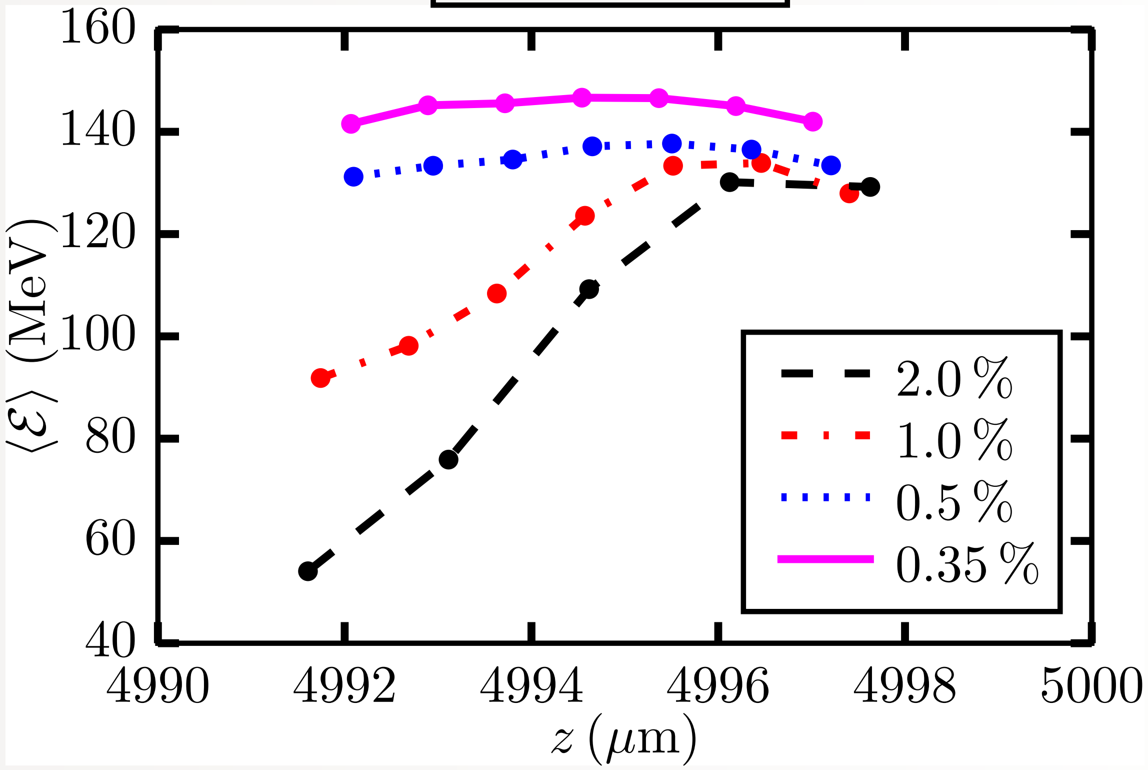


@ 2.7mm



- correlation between average energy and position

@ 5.0mm



- the decrease of C_{N_2} increases the phase space rotation → reduce the energy spread
- if $C_{N_2} \leq 0.35\%$, the degree of phase space rotation becomes large → degrade the energy spread

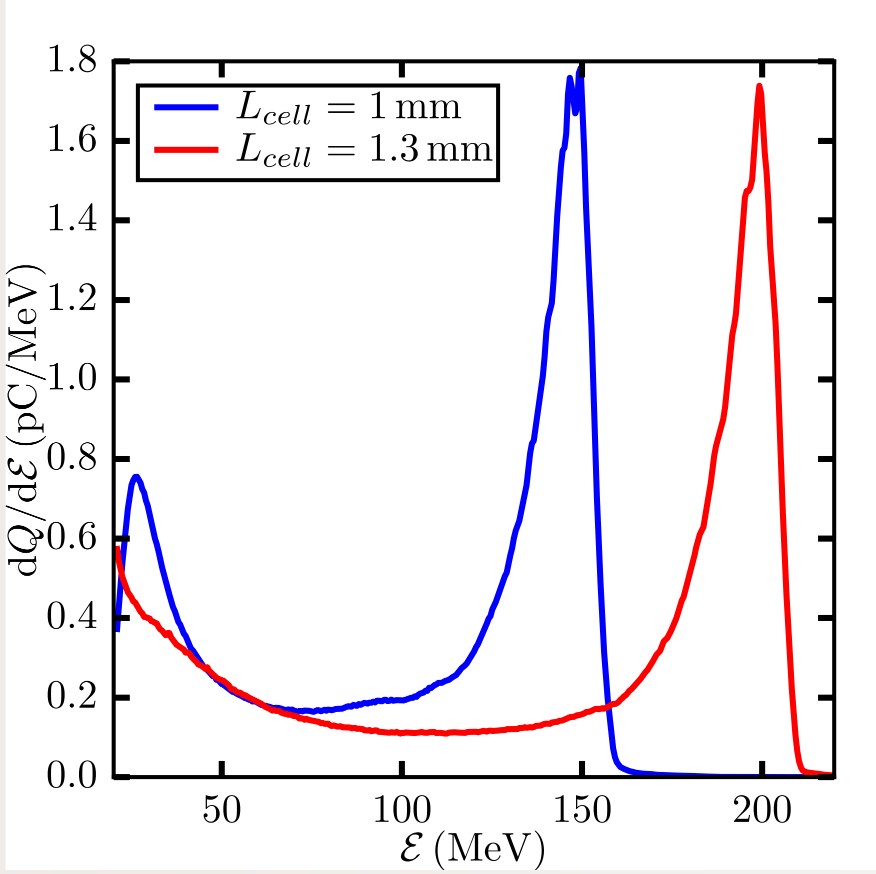
Electron beam energy can be tuned while preserving other beam properties

Results summary

C_{N_2} (%)	Q (pC)	$\langle \mathcal{E} \rangle$ (MeV)	$\Delta\mathcal{E}_{rms}/\langle \mathcal{E} \rangle$ (%)	θ_x (mrad)	θ_y (mrad)	$\varepsilon_{x,n}$ (mm.mrad)	$\varepsilon_{y,n}$ (mm.mrad)
0.35	27	142	3.8	2.1	2.9	0.8	1.8
0.5	37	135	5.0	2.8	3.1	1.1	1.9
1.0	72	113	14.7	3.7	4.0	1.8	2.2
2.0	107	93	29.1	4.6	5.6	2.5	3.8

} optimal values

Extending cell length to yield a higher energy electron bunch



- For C_{N_2}=0.35%, L_{cell}=1 mm → 1.3 mm
  - $\langle \mathcal{E} \rangle$ =142→ 196 MeV,
  - $\Delta\mathcal{E}_{rms}/\langle \mathcal{E} \rangle$ = 3.8→ 3.2%,
  - Q remains at 27 pC,
  - θ_x = 2.1→ 2.2 mrad,
  - θ_y = 2.9→ 3.1 mrad,
  - $\varepsilon_{x,n}$ = 0.8→ 1.3 mm.mrad,
  - $\varepsilon_{y,n}$ =1.8→ 2.3 mm.mrad

Conclusion and perspective

- **Space charge effects have demonstrated to be beneficial** in the generation of a high quality electron bunch for an injector

- the present laser plasma configuration with C_{N_2}=0.35% has proven to be **robust for the tuning of electron bunch energy while preserving other properties**

- In perspective, simulations with realistic laser spatial-temporal profile measurements

P. Lee et al., PRAB in preparation

Thank you