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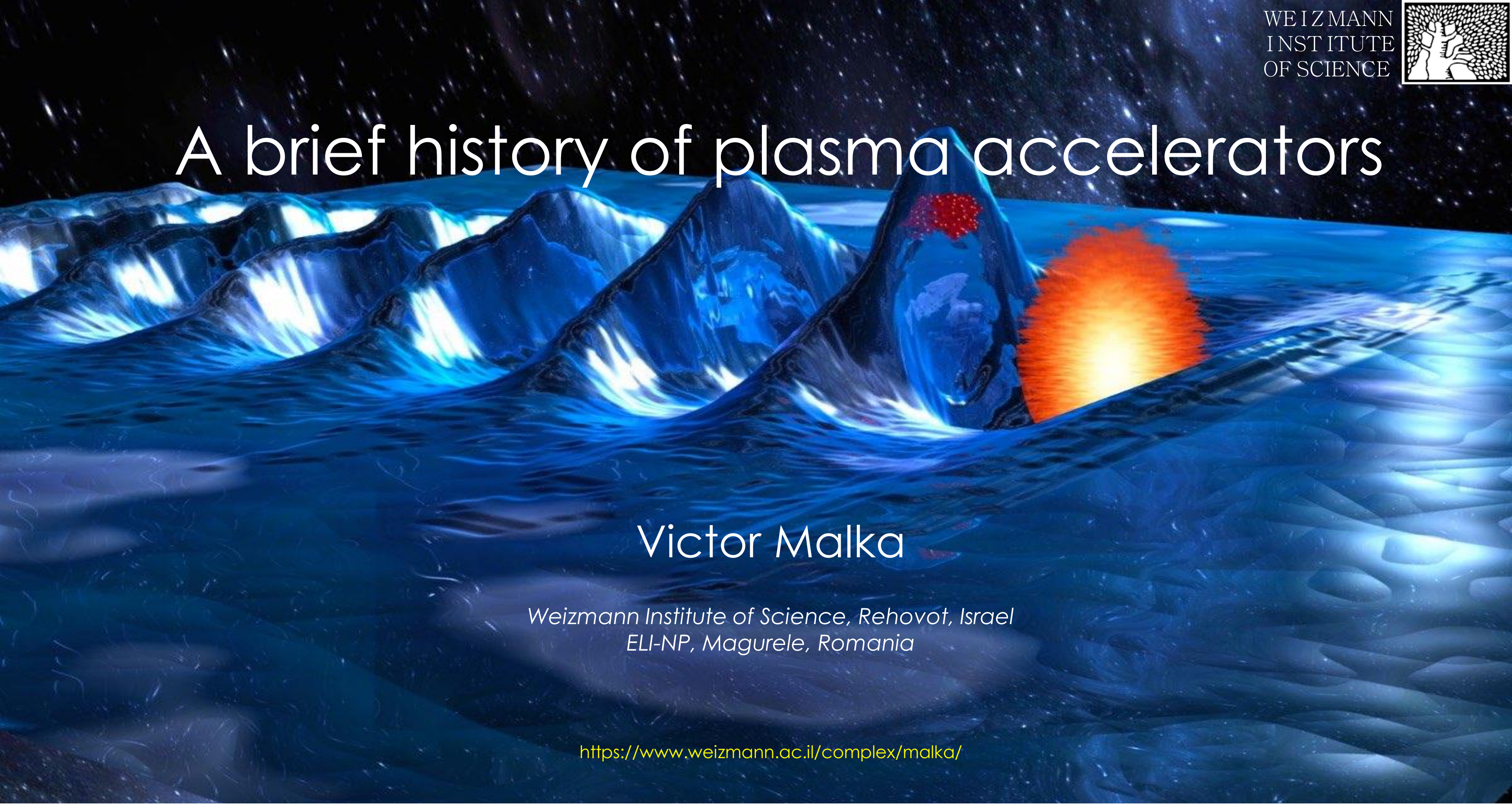


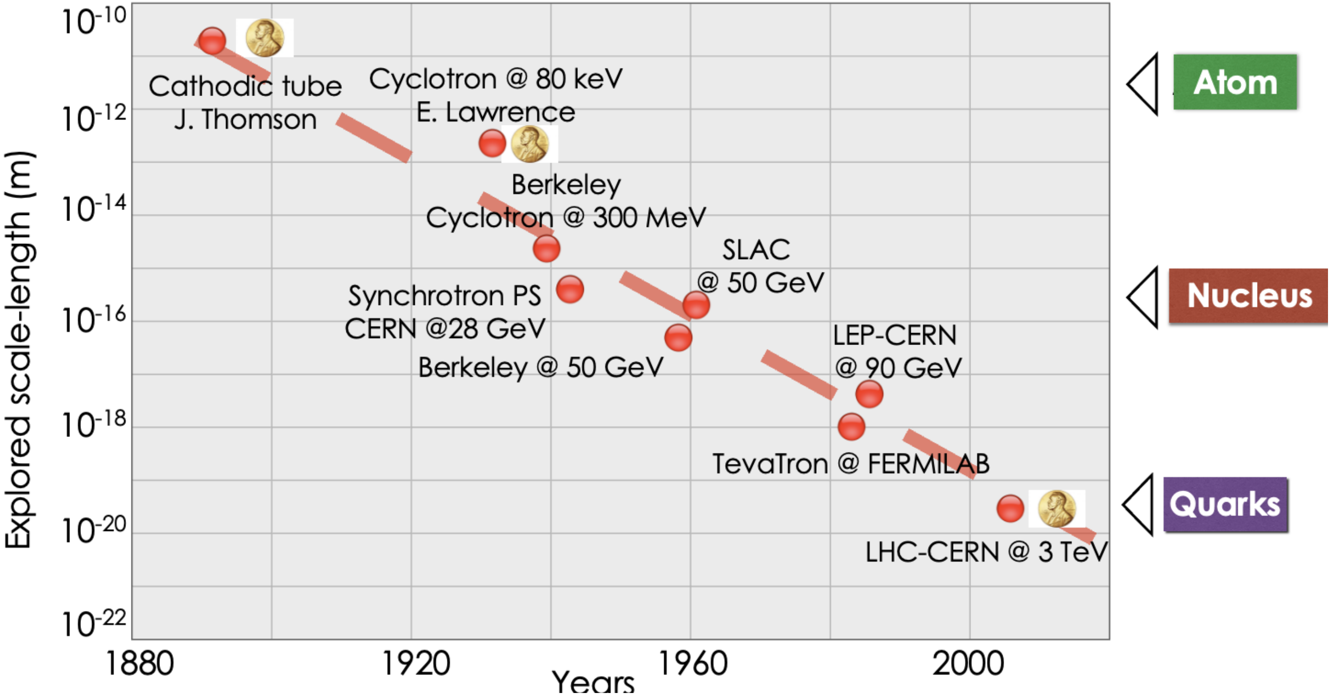
A brief history of plasma accelerators

Victor Malka

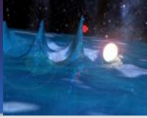
Weizmann Institute of Science, Rehovot, Israel
ELI-NP, Magurele, Romania

https://www.weizmann.ac.il/complex/malka/

Accelerators: One century of exploration of the infinitively small



Industrial Market for Accelerators



The development of state of the art accelerators for HEP has lead to :
research in other field of science (light source, spallation neutron sources…)
industrial accelerators (cancer therapy, ion implant., electron cutting &welding...)

Application	Total syst. (2007) approx.	System sold/yr	Sales/yr (M$)	System price (M$)
Cancer Therapy	9100	500	1800	2.0 - 5.0
Ion Implantation	9500	500	1400	1.5 - 2.5
Electron cutting and welding	4500	100	150	0.5 - 2.5
Electron beam and X rays irradiators	2000	75	130	0.2 - 8.0
Radio-isotope production (incl. PET)	550	50	70	1.0 - 30
Non destructive testing (incl. Security)	650	100	70	0.3 - 2.0
Ion beam analysis (incl. AMS)	200	25	30	0.4 - 1.5
Neutron generators (incl. sealed tubes)	1000	50	30	0.1 - 3.0
Total	27500	1400	**3680**	

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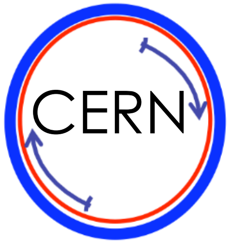
Plasma Accelerators : motivations

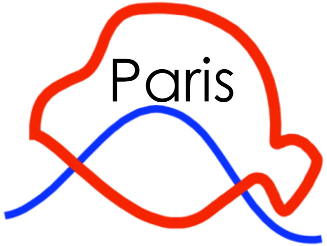
E-field$_{max}$ ≈ few 10 MeV /meter (Breakdown)
R>R$_{min}$ Synchrotron radiation

→ Energy ↗ → Length ↗ → Cost ↗

LHC
27 km



≈



Circle road
31 km

☐ → New medium : the plasma

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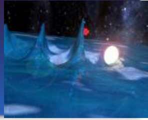
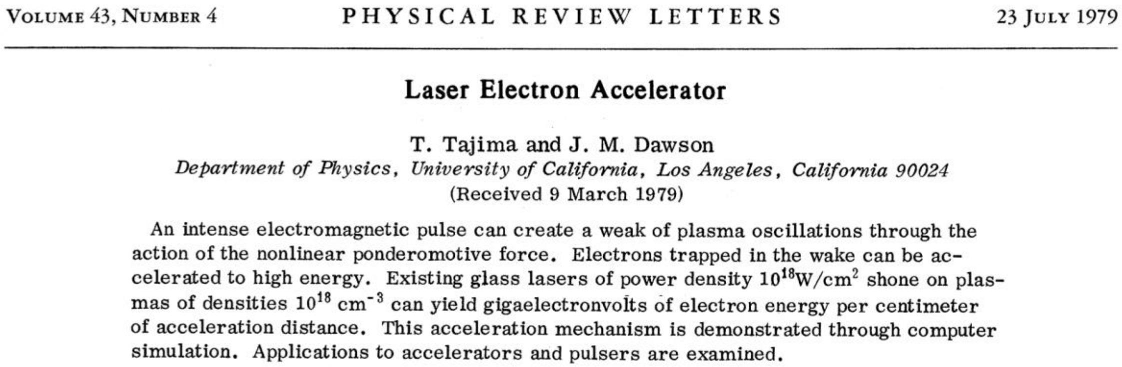
It starts with…



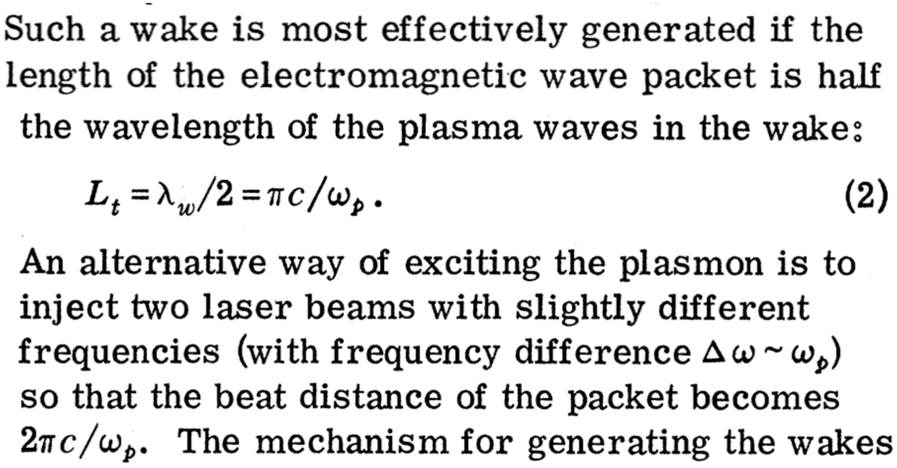


Volume 43, Number 4 PHYSICAL REVIEW LETTERS 23 July 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.



Such a wake is most effectively generated if the length of the electromagnetic wave packet is half the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p \, . \tag{2}$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes

=> Laser wakefield

=> Laser beatwave

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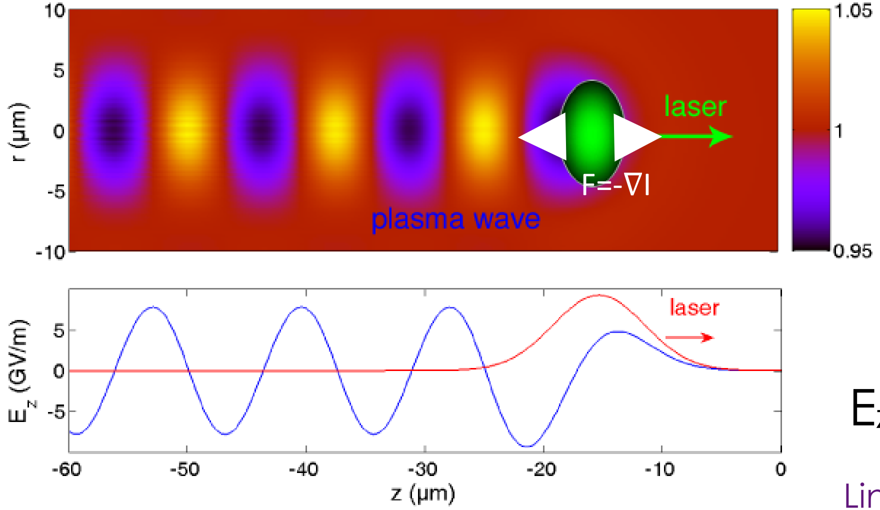
The linear wakefield regime: GV/m electric field

The laser wake field : broad resonance condition

$T_{laser} \sim \pi/\omega_p$ with $\omega_p \sim n_e^{1/2}$ i.e. $\lambda_p \sim 1/n_e^{1/2}$

electron density perturbation & longitudinal wakefield



$v_{phase}^{epw} = v_g^{laser} \sim c$

wave in the wake of a boat

$$E_z\,(\mathrm{GV/m}) \approx \delta n/n \times \sqrt{n}$$

Linear wakefield: E_z = 1 GV/m for 1% density Perturbation at 10^{18} cc^{-1}

T. Tajima and J. Dawson, PRL **43**, 267 (1979)

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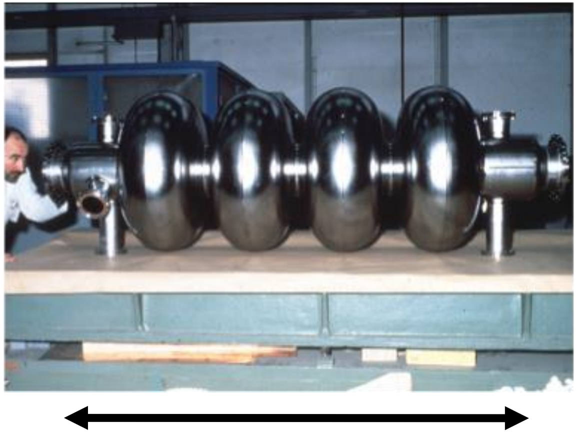
Funded by the European Union

Compactness of Laser Plasma Accelerators

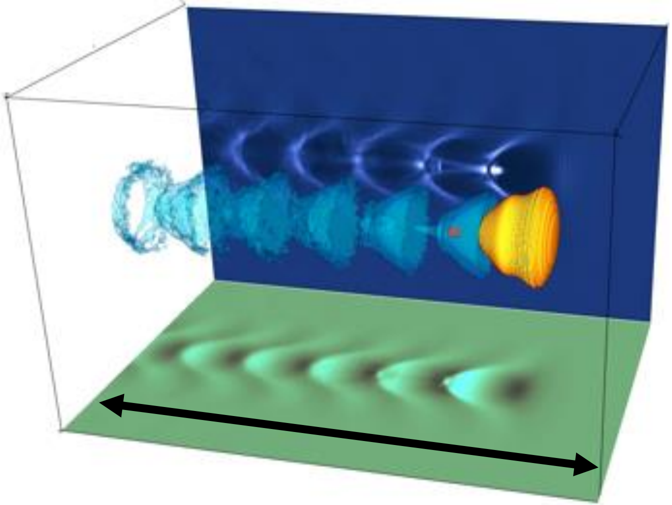
RF Cavity



1 m => 50 MeV Gain

Electric field < 100 MV/m

Plasma Cavity



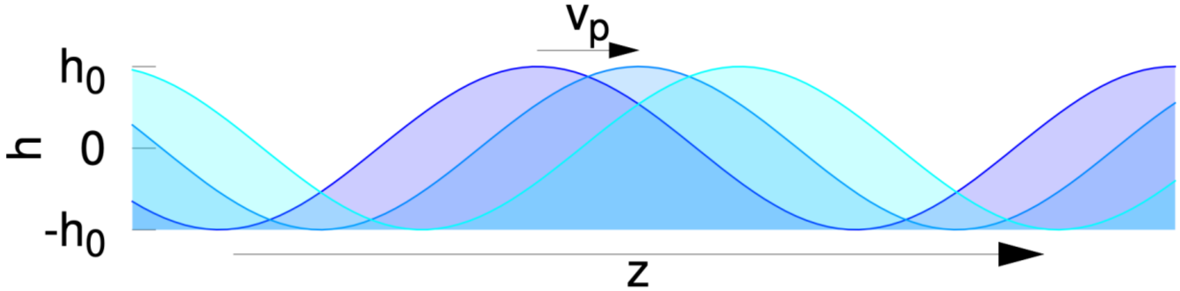
1mm => 100 MeV

Electric field > 100 GV/m

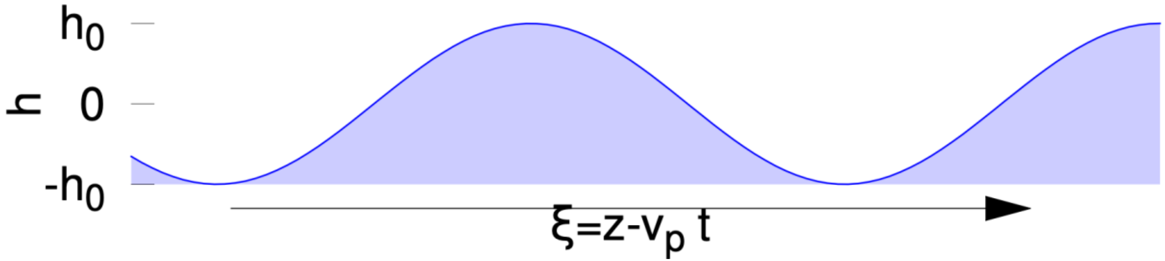
A. Pukhov & J. Meyer-ter-Vehn, Appl. Phys. B **74**, 355-361 (2002)

V. Malka *et al.*, Science **298**, 1596 (2002)

Injection criteria : the surfer

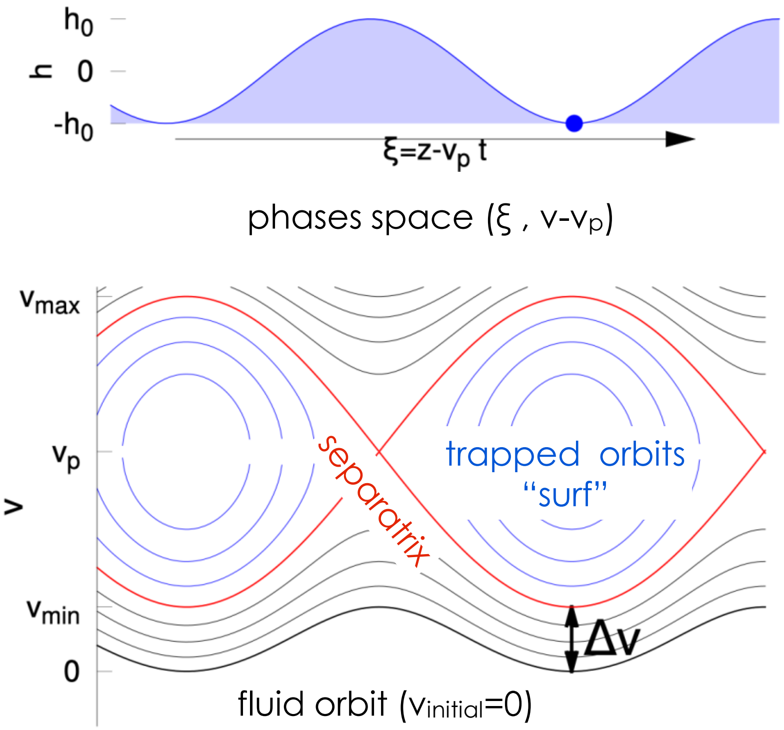


in the terrestrial reference frame
$h = h_0\cos(z - v_p t)$



in the wawe reference frame
$h = h_0\cos(\xi)$

Injection criteria : the surfer

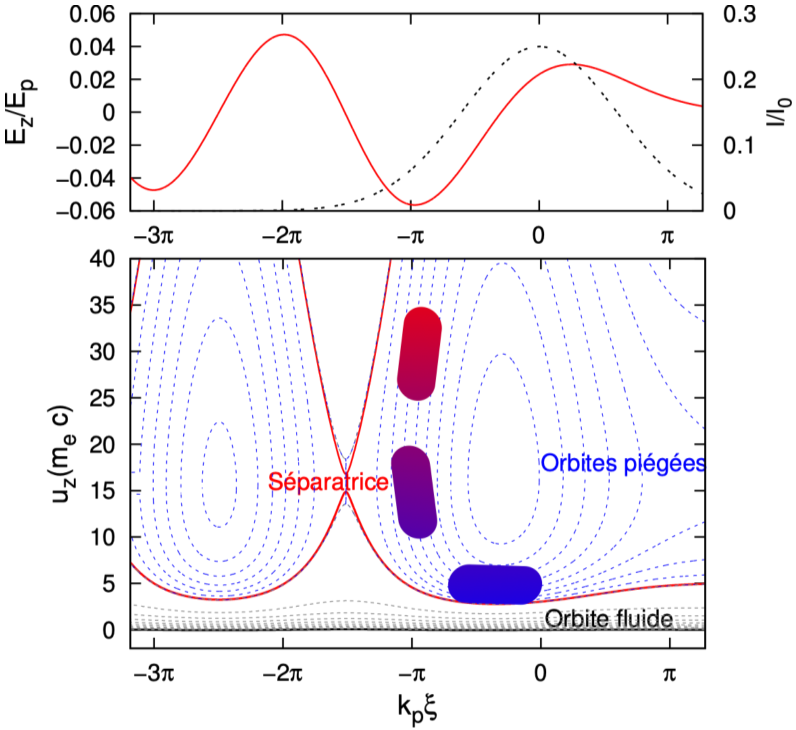


conclusions :

- Trapped orbits allow higher energy gain

- One needs to transmit enough velocity ΔV

Injection criteria : the surfer



In plasma wave :

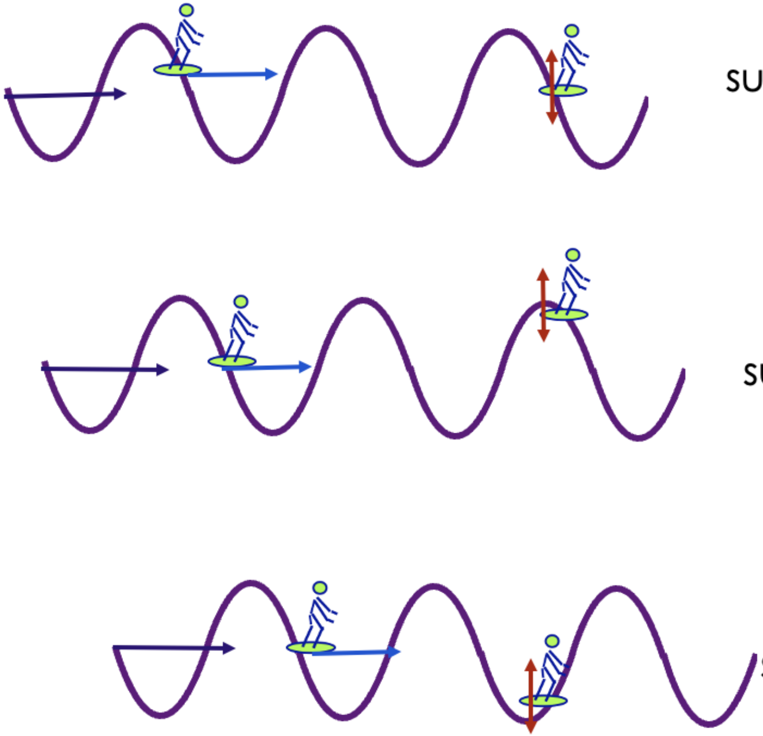
- E field is not homogenous
- Volume is phase space is conserved
- very small initial volume

external injection :

- Size≈ µm
- Length≈ µm (fs)
- Synchronization ≈ fs
- Controle ?

=> very challenging with conventional accelerator

Trapping energy : analogy electron/surfer



surfer with enough initial velocity

surfer initially at rest

surfer with enough initial velocity

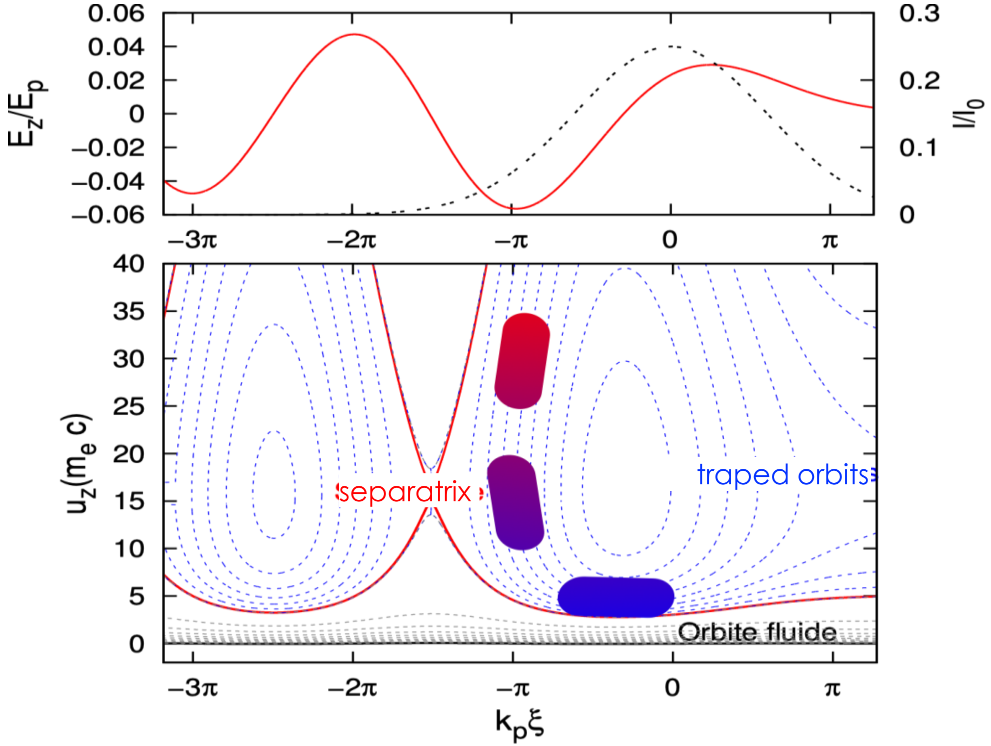
surfer initially at rest

surfer with enough initial velocity

surfer initially at rest

Trapping energy : analogy electron/surfer

High beam quality: precise controlled on inject.



In plasma wave :

- E field is not homogenous
- Volume is phase space is conserved
- very small initial volume

External injection :

- Size≈ µm
- Length≈ µm (fs)
- Synchronization ≈ fs
- Controle ?

=> very challenging with conventional accelerator

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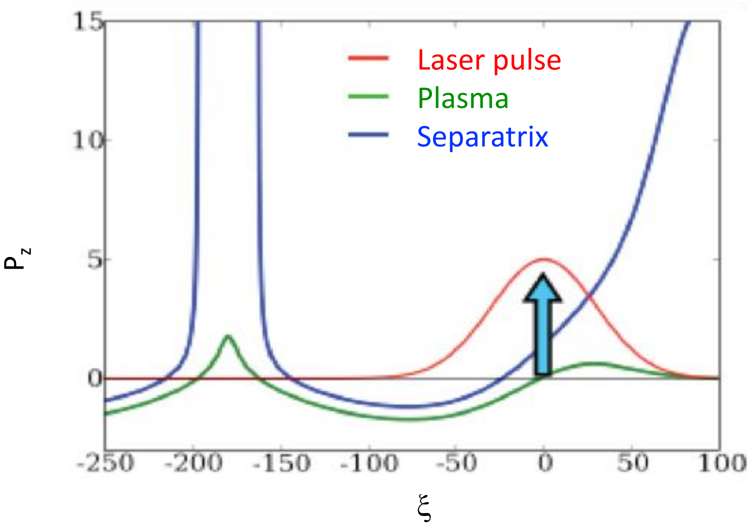
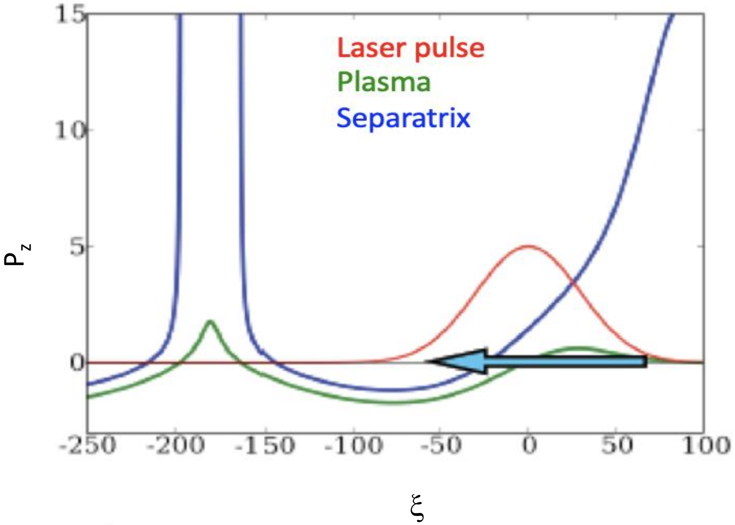
Injection schemes: how to cross the separatrix

Hot injection: heating process of electrons



Colliding laser pulses: linear polarisation
External injection, Wavebreaking

Cold injection: dephasing of electrons

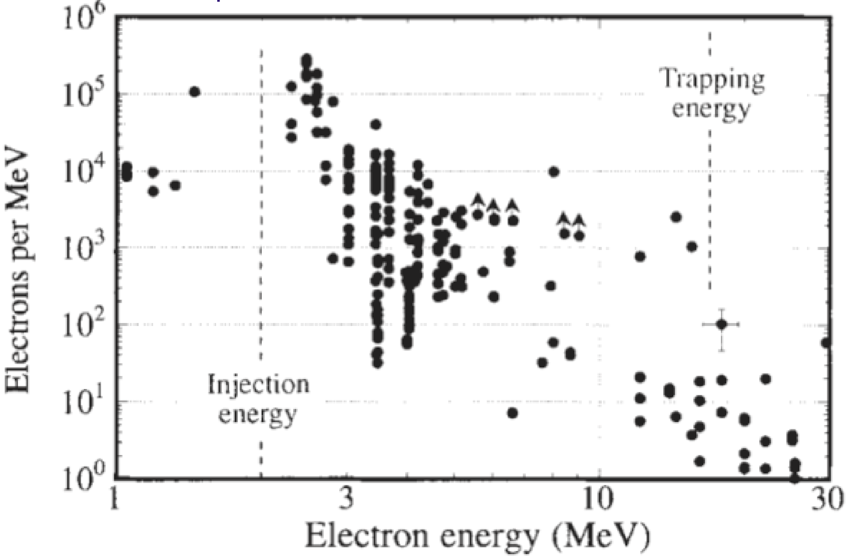


Colliding laser pulses: circular polarisation
Longitunal injection/self truncated ionisation
Transverse wave breaking

V. Malka, Phys. of Plasmas **19**, 055501 (2012)

1992-1994 Accelerated electrons in LBWF

The 2-MeV electrons are accelerated up to ≈ 28 MeV
Electron spectra indicate an E_{field} of ≈ 2.8 GV/m

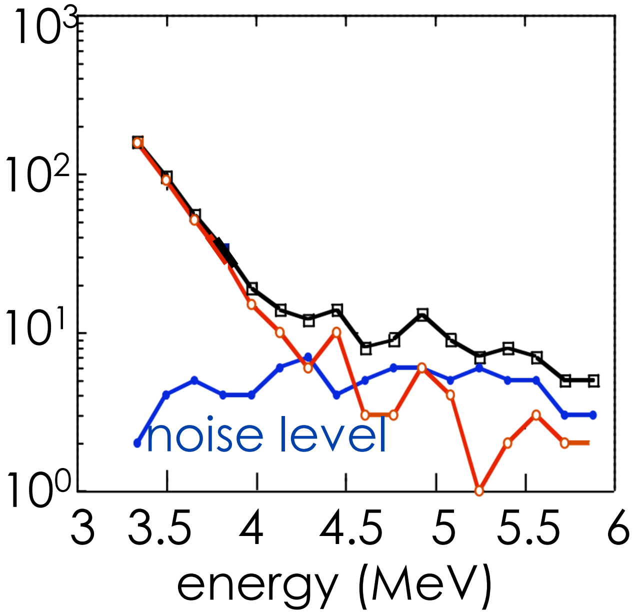


M. Everett *et al.*, Nature 1994

Electron gain demonstration Few MeV's: Kitagawa *et al.* PRL 1992, Clayton *et al.* PRL 1993, N. A. Ebrahim *et al.*, J. Appl. Phys.1994, Amiranoff *et al.* PRL 1995

1998 Accelerated electrons in LWF

The 3-MeV electrons are accelerated up to ≈ 4.5 MeV
Electron spectra indicate an E_{field} of ≈ 1.4 GV/m



F. Amiranoff *et al.*, PRL 1998

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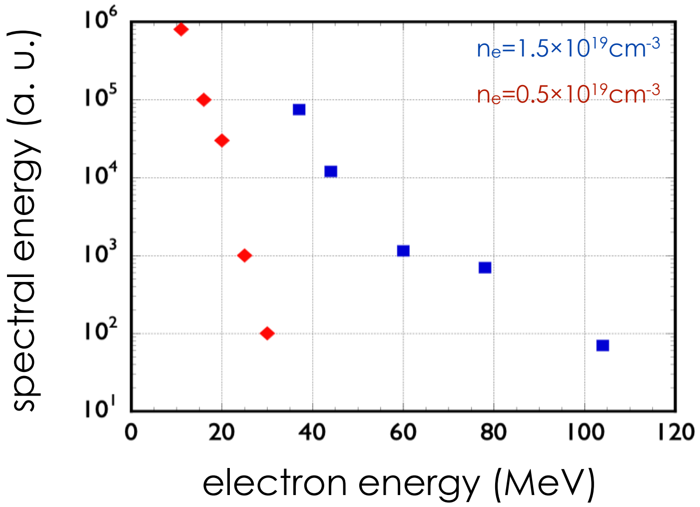
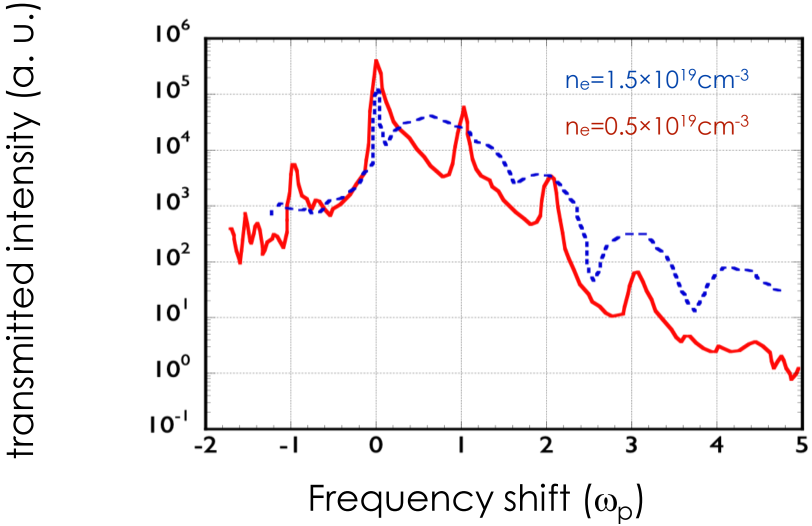
1995 Accelerated electrons in SLWF





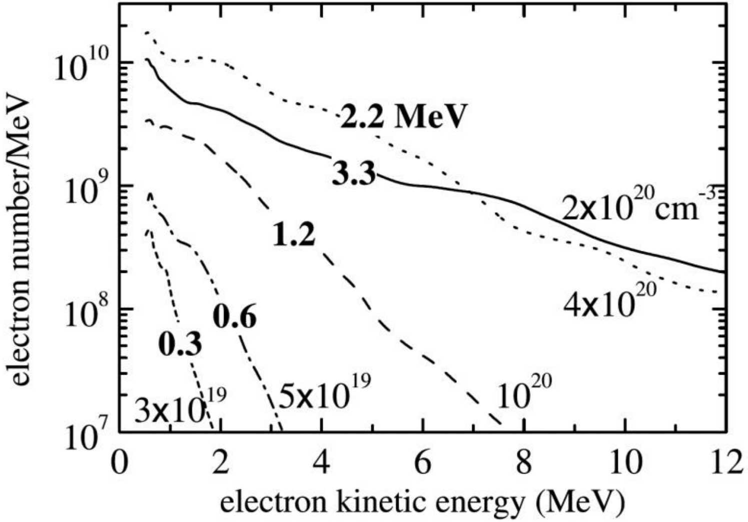
- Multiple satellites : high amplitude plasma waves
- Broadening at higher densities
- Loss of coherence of the relativistic plasma waves

A. Modena *et al.*, Nature (1995)

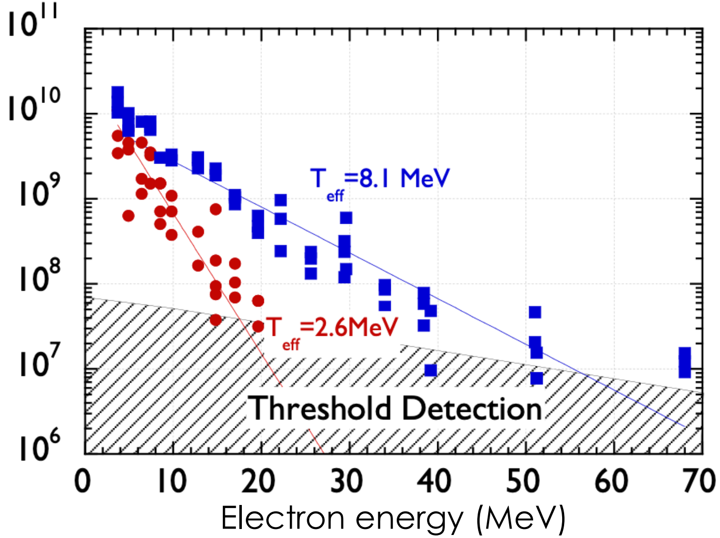
DLA/LPWF debate in 1999/2001

Spectra : E_{max} increases/decreases when n_e decreases

$n_e=3\times10^{19}\text{cm}^{-3}$ - $2\times10^{20}\text{cm}^{-3}$,
τ_L=200fs, E=0.25J, $I_L= 4\times10^{18}\text{W/cm}^2$

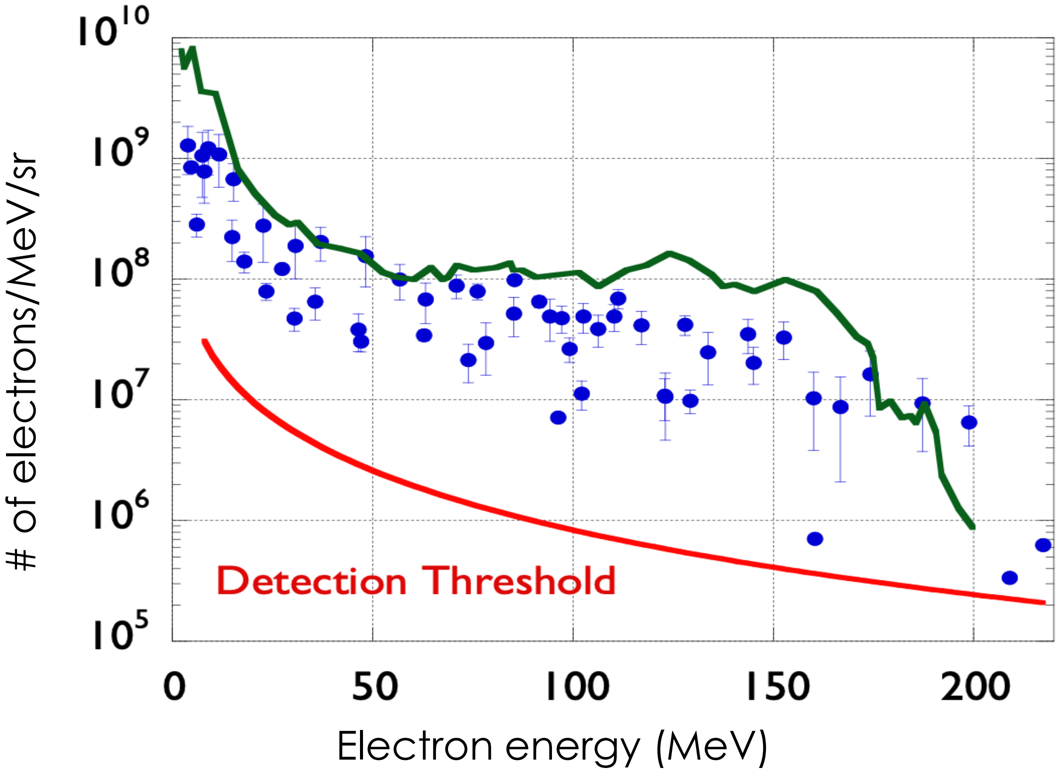


$n_e=5\times10^{19}\text{cm}^{-3}$ & $1.5\times10^{20}\text{cm}^{-3}$,
τ_L=35fs, E=0.6J, $I_L= 2\times10^{19}\text{W/cm}^2$



C. Gahn *et al.*, PRL **83**, 23 (1999), V. Malka *et al.*, Phys. of Plasmas **8**, 6 (2001)

2002 the NL regime: 100s GV/m electric field



Parameters: $n_e=1.5\times10^{19}\text{cm}^{-3}$,

$\tau_L=35\text{fs}$,

E=0.6J,

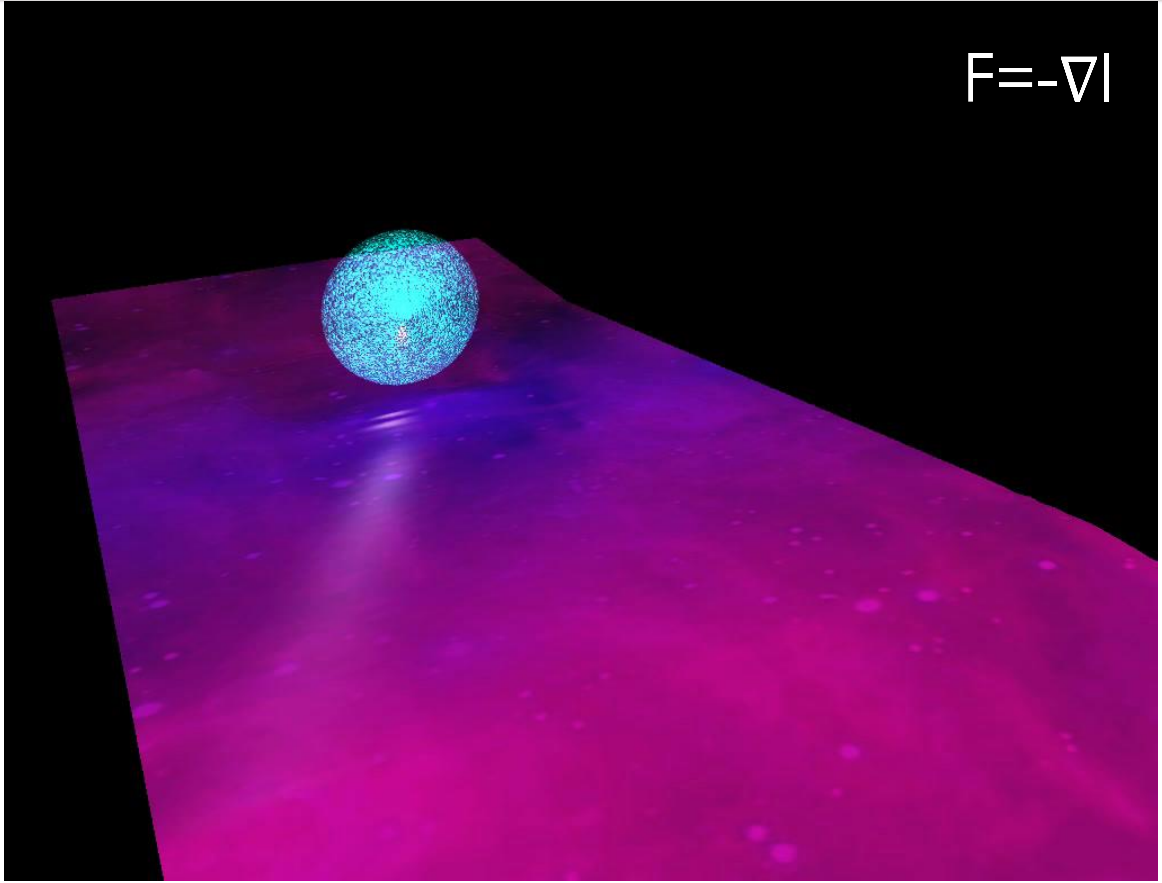
$I_L= 1\times10^{18}\text{W/cm}^2$

with $k_p w_0>1$

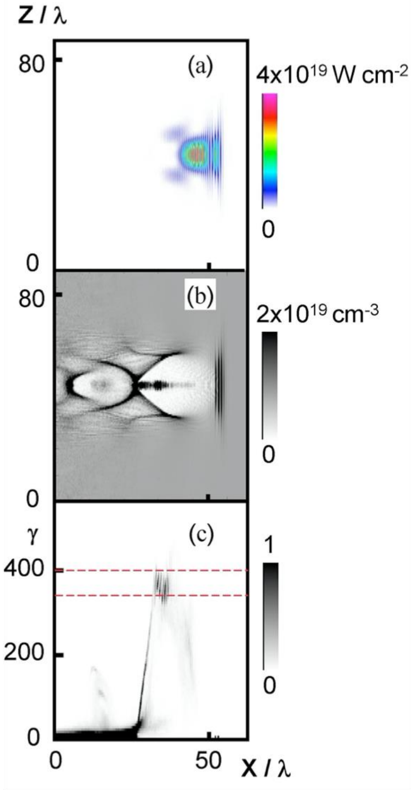
*CARE project

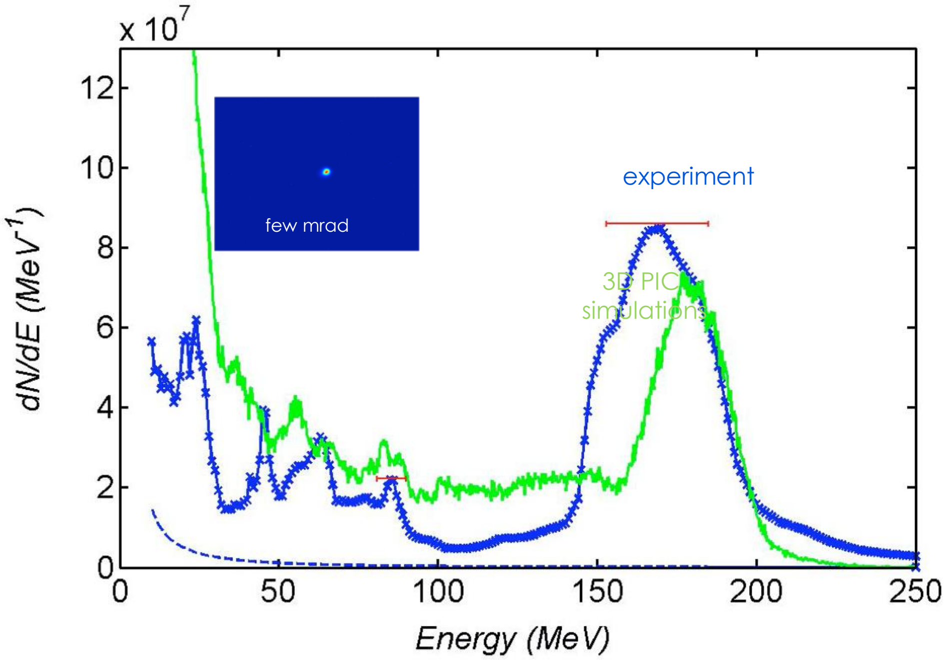
V. Malka *et al.*, Science **298**, 1596 (2002)

The Forced laser wakefield



2004 The Bubble regime : theory/experiments

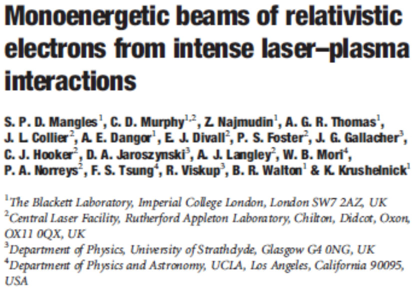




Experimental parameters : $E=1J$, $\tau_L=30fs$, $\lambda_L=0.8\mu m$, $I_L=3.2\times10^{19} W/cm^2$, $n_e=6\times10^{18} cm^{-3}$

J. Faure *et al.*, Nature **431**, 7008 (2004)

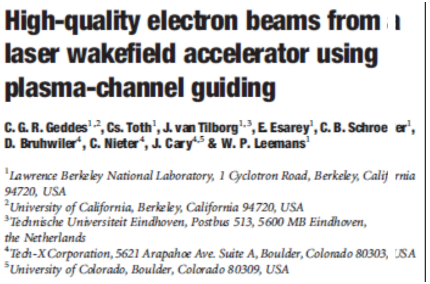
2004 The Dream Beam



Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

S. P. D. Mangles[1], C. D. Murphy[1,2], Z. Najmudin[1], A. G. R. Thomas[1], J. L. Collier[2], A. E. Dangor[1], E. J. Divall[2], P. S. Foster[2], J. G. Gallacher[3], C. J. Hooker[2], D. A. Jaroszynski[3], A. J. Langley[2], W. B. Mori[4], P. A. Norreys[2], F. S. Tsung[4], R. Viskup[3], B. R. Walton[1] & K. Krushelnick[1]

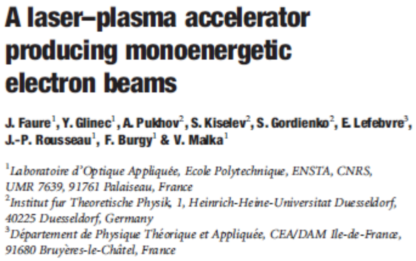
[1]The Blackett Laboratory, Imperial College London, London SW7 2AZ, UK
[2]Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK
[3]Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK
[4]Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA



High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

C. G. R. Geddes[1,2], Cs. Toth[1], J. van Tilborg[1,3], E. Esarey[1], C. B. Schroeder[1], D. Bruhwiler[4], C. Nieter[4], J. Cary[4,5] & W. P. Leemans[1]

[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[2]University of California, Berkeley, California 94720, USA
[3]Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, the Netherlands
[4]Tech-X Corporation, 5621 Arapahoe Ave. Suite A, Boulder, Colorado 80303, USA
[5]University of Colorado, Boulder, Colorado 80309, USA

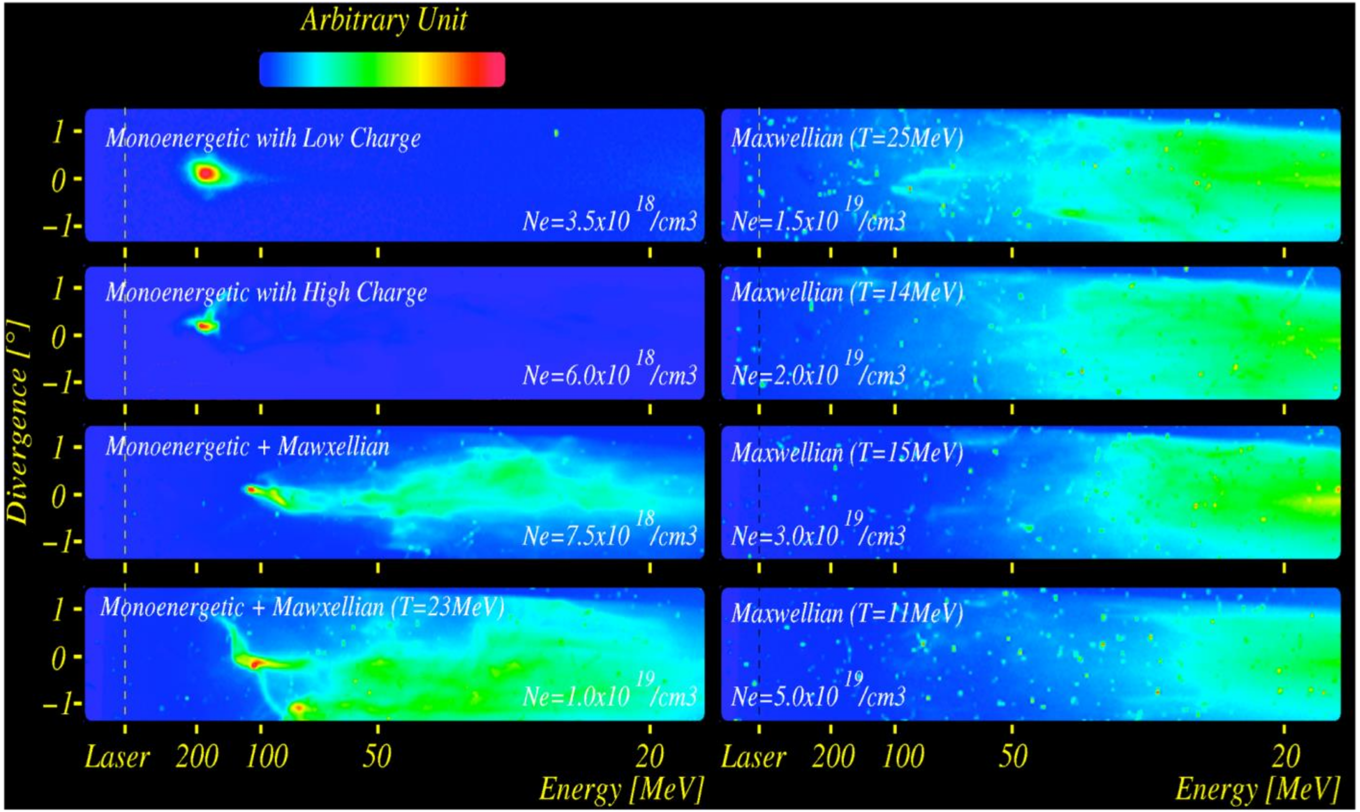


A laser–plasma accelerator producing monoenergetic electron beams

J. Faure[1], Y. Glinec[1], A. Pukhov[2], S. Kiselev[2], S. Gordienko[2], E. Lefebvre[3], J.-P. Rousseau[1], F. Burgy[1] & V. Malka[1]

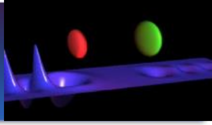
[1]Laboratoire d'Optique Appliquée, Ecole Polytechnique, ENSTA, CNRS, UMR 7639, 91761 Palaiseau, France
[2]Institut fur Theoretische Physik, 1, Heinrich-Heine-Universitat Duesseldorf, 40225 Duesseldorf, Germany
[3]Département de Physique Théorique et Appliquée, CEA/DAM Ile-de-France, 91680 Bruyères-le-Châtel, France

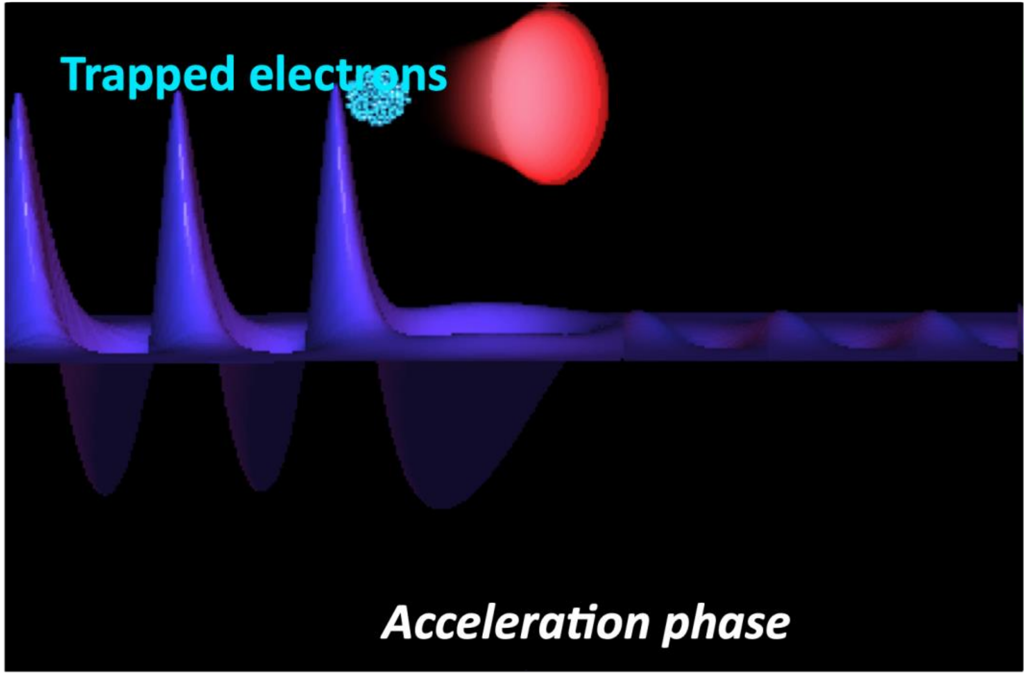
SMLWF => FLWF => Bubble regime



V. Malka *et al.*, Phys. of Plasmas **12**, 5 (2005)

Colliding Laser Pulses Scheme

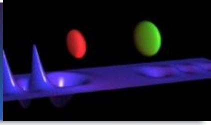




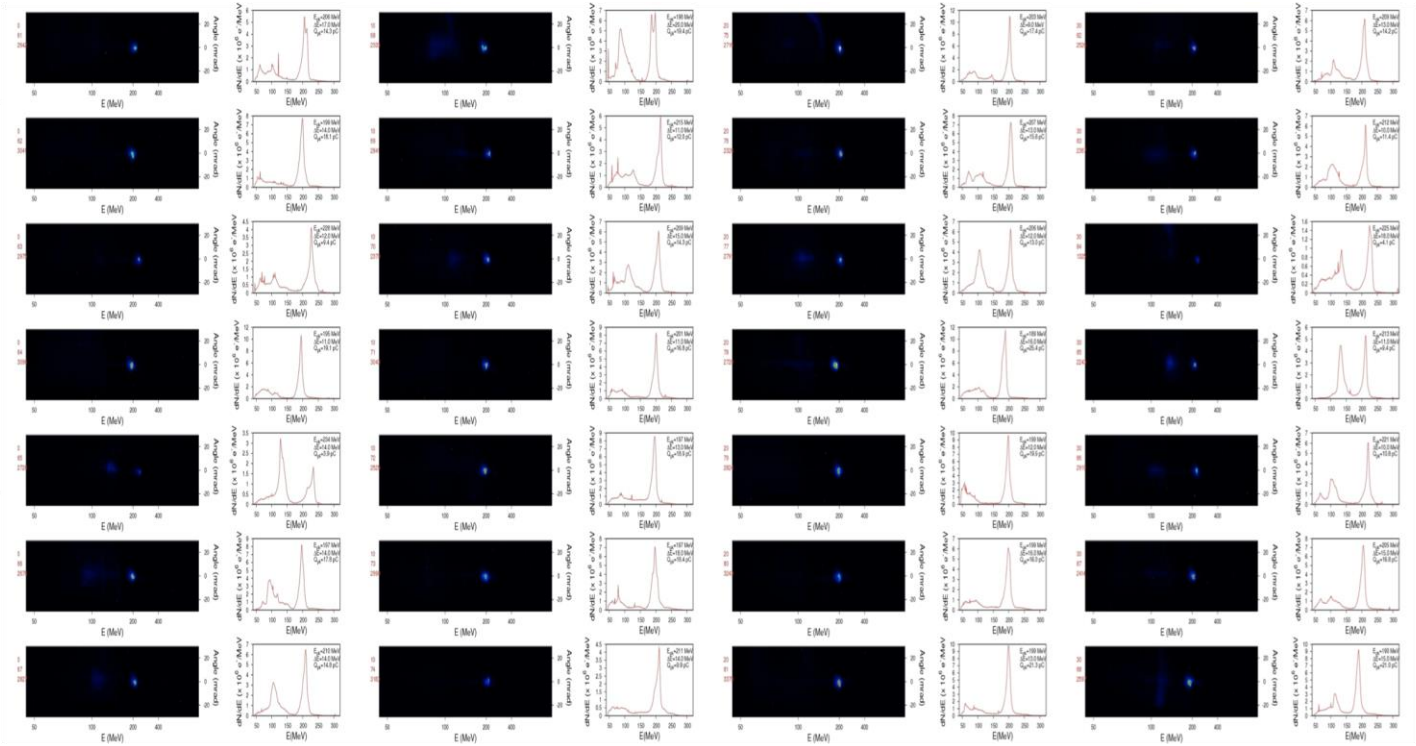
The first laser creates the accelerating structure
A second laser beam is used to heat electrons

E. Esarey *et al.*, PRL **19**, 2682 (1997)

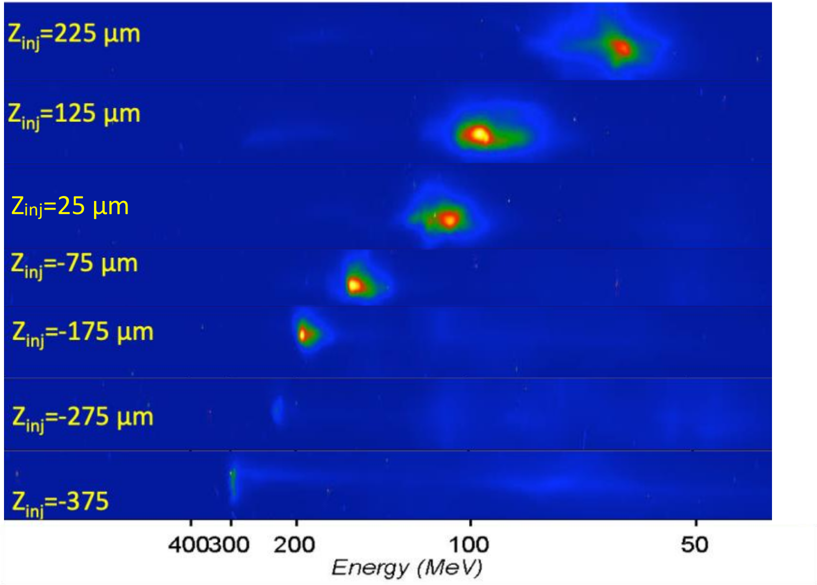
Towards a Stable Laser Plasma Accelerators

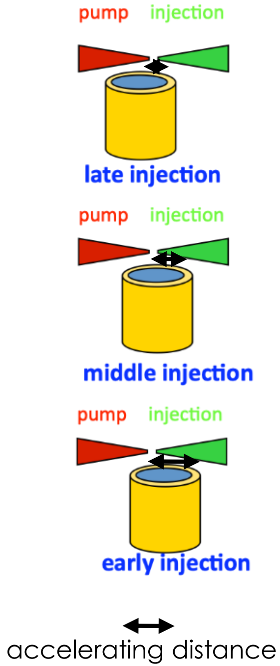


Series of 28 consecutive shots with : a_0=1.5, a_1=0.4, n_e=5.7×$10^{18}$$cm^{-3}$



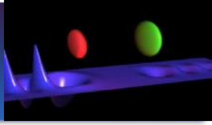
Tunability of the electrons energy





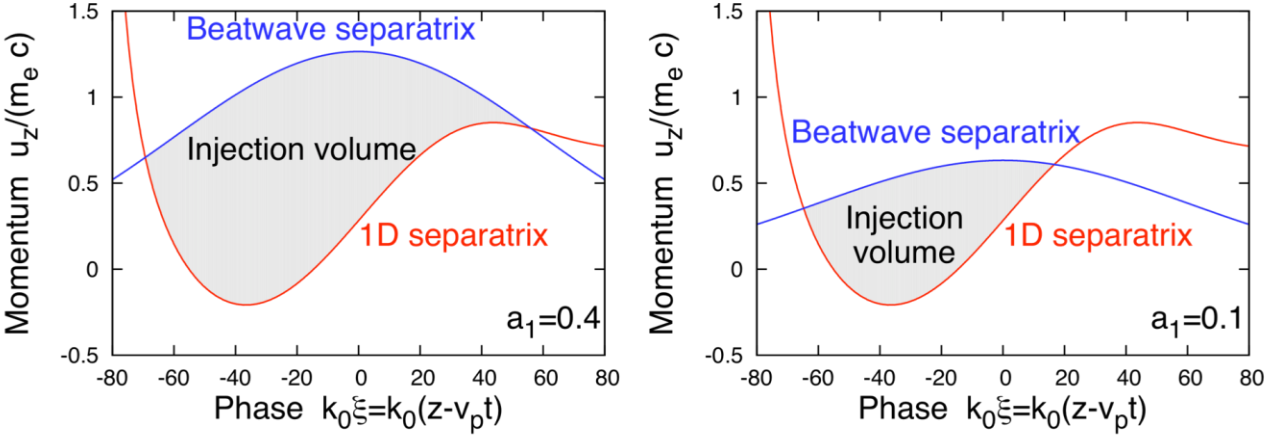
J. Faure *et al.*, Nature **444**, 737 (2006)

Tunability of charge & energy spread



Charge : controlling electrons heating processes => smaller $a_{inj.}$ means less heating and less trapping

Energy spread : Decreasing the phase space volume V_{trap} of trapped electrons by reducing $a_{inj.}$ or by reducing $c\tau/\lambda_p$ by changing n_e (i.e λ_p)

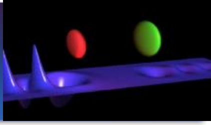


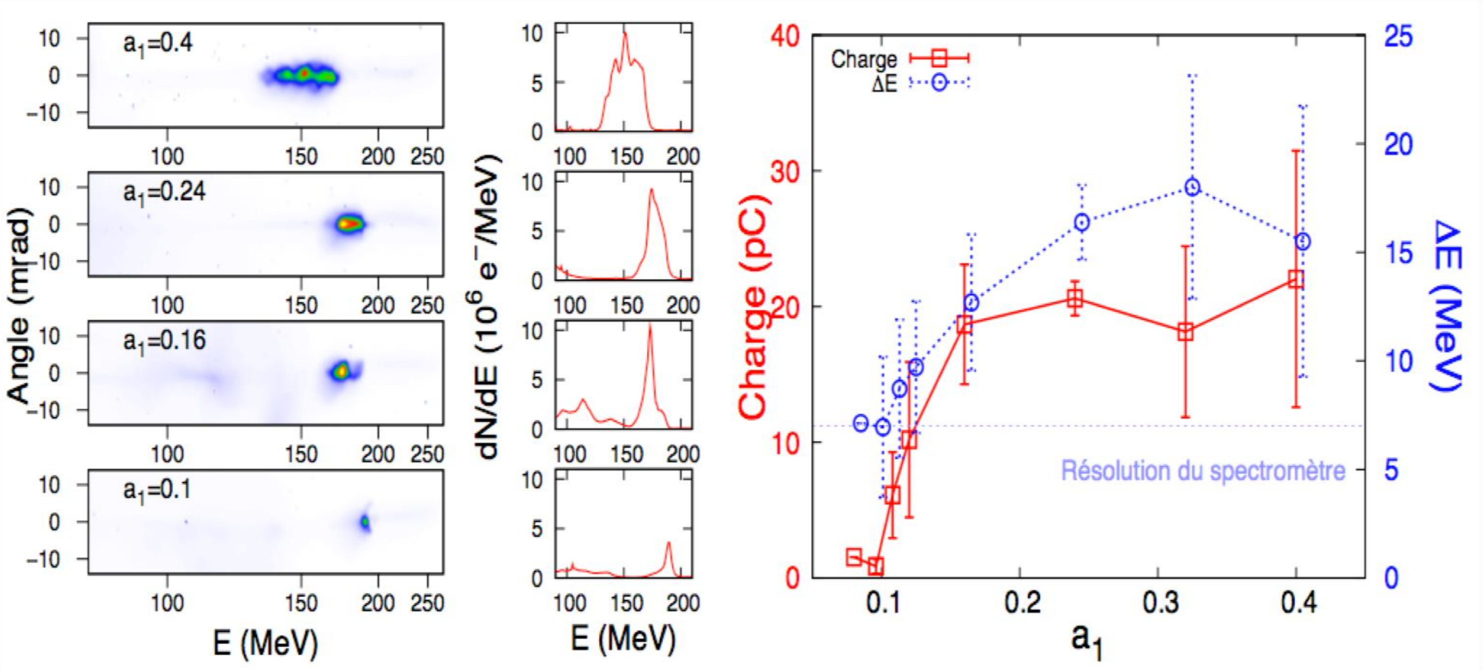
Evolution of injection volume with a_1 for $a_0 = 2$, $n_e = 7\times10^{18}\text{cm}^{-3}$.

Fields are computed for the 1D case and the beatwave separatrix corresponds to the circular polarization case.

In practice, energy spread and charge are correlated: Decreasing a_1 decreases the charge but also V_{trap}, and in consequence the energy spread

Tuning charge & energy spread with $I_{inj.laser}$

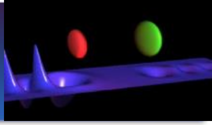


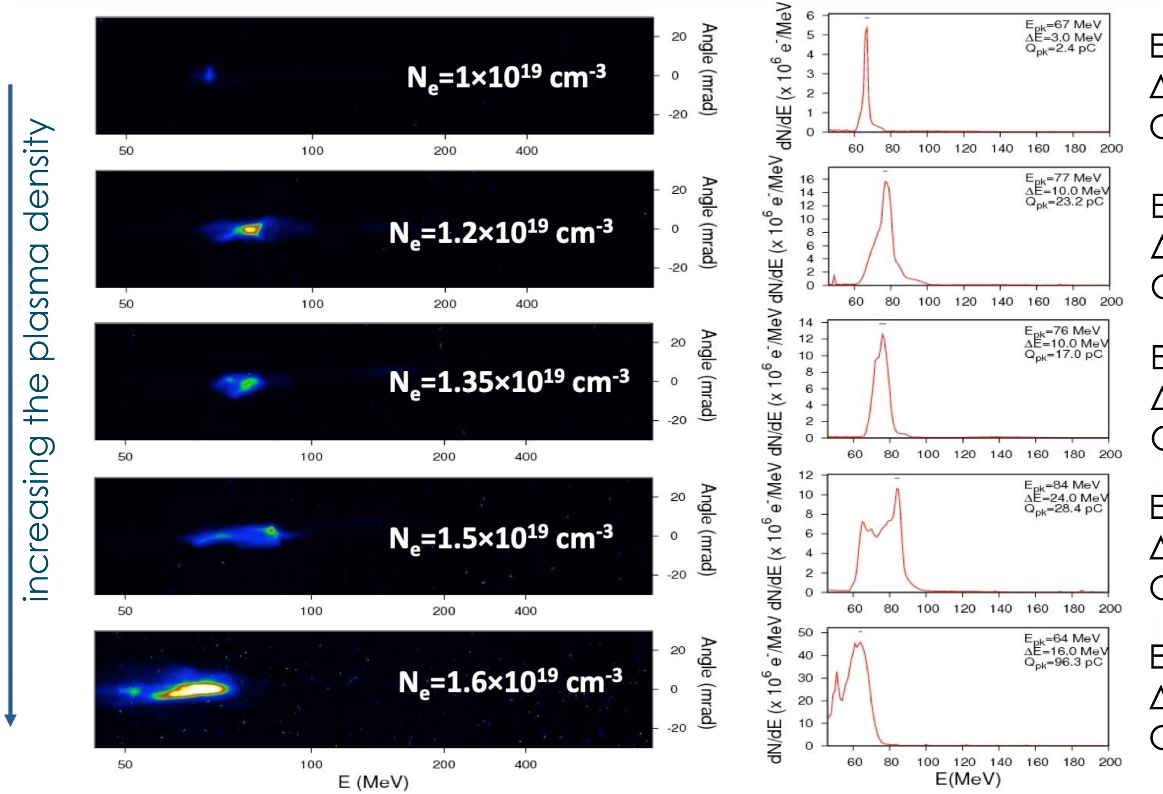


Charge from 60 pC to 5 pC, ΔE from 20 to 5 MeV

C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 164801 (2009)

Tuning charge & energy spread with n_e





E=67 MeV
ΔE=3 MeV
Q_{pk}=2.4pC

E=77 MeV
ΔE=10 MeV
Q_{pk}=23.2pC

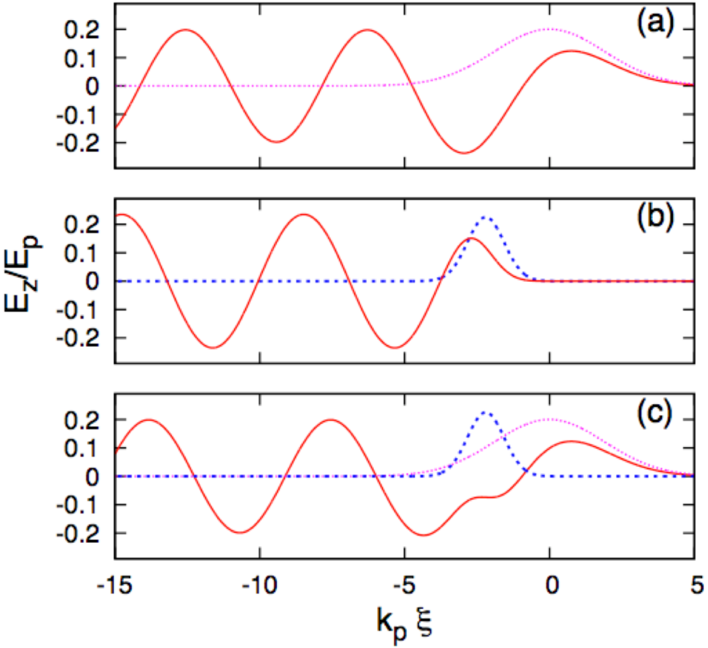
E=76 MeV
ΔE=10.0 MeV
Q_{pk}=17pC

E=84 MeV
ΔE=24 MeV
Q_{pk}=25.4pC

E=64 MeV
ΔE=16 MeV
Q_{pk}=96pC

Beam loading effect

Parameters: n_e=1.5 10^{19}cm^{-3},τ =35fs, E=0.6J, I=2 10^{18} W/cm^2



Laser wakefield

n_e=7 10^{18}cm^{-3},τ = 30fs, a_0 = 0.5

E-beam wakefield

n_b/n_e=0.11, τ = 10fs, d_{FWHM}=4μm (Q=7pC)

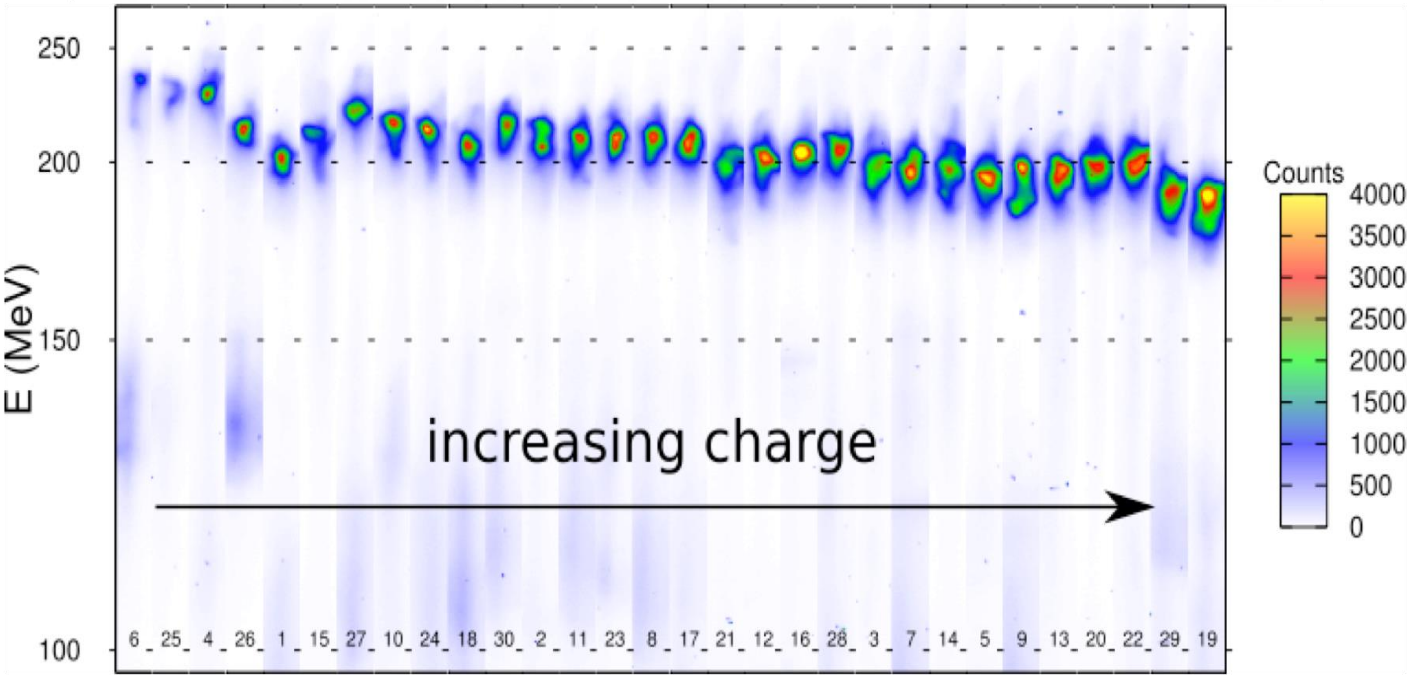
The end of the bunch experiments a modified wakefield

Limitation of the accelerated charge
Influence on energy and energy spread

Observables : correlation charge/energy spread/energy

T. Katsouleas *et al.*, (1987), M. Tzoufras *et al.*, Phys. Rev. Lett.,**101** (2008)

Beam loading effect



Clear correlation !

Nb: very few electrons at low energy
$\delta E/E = 5\%$ limited by the spectrometer

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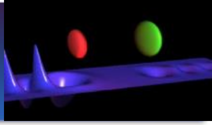
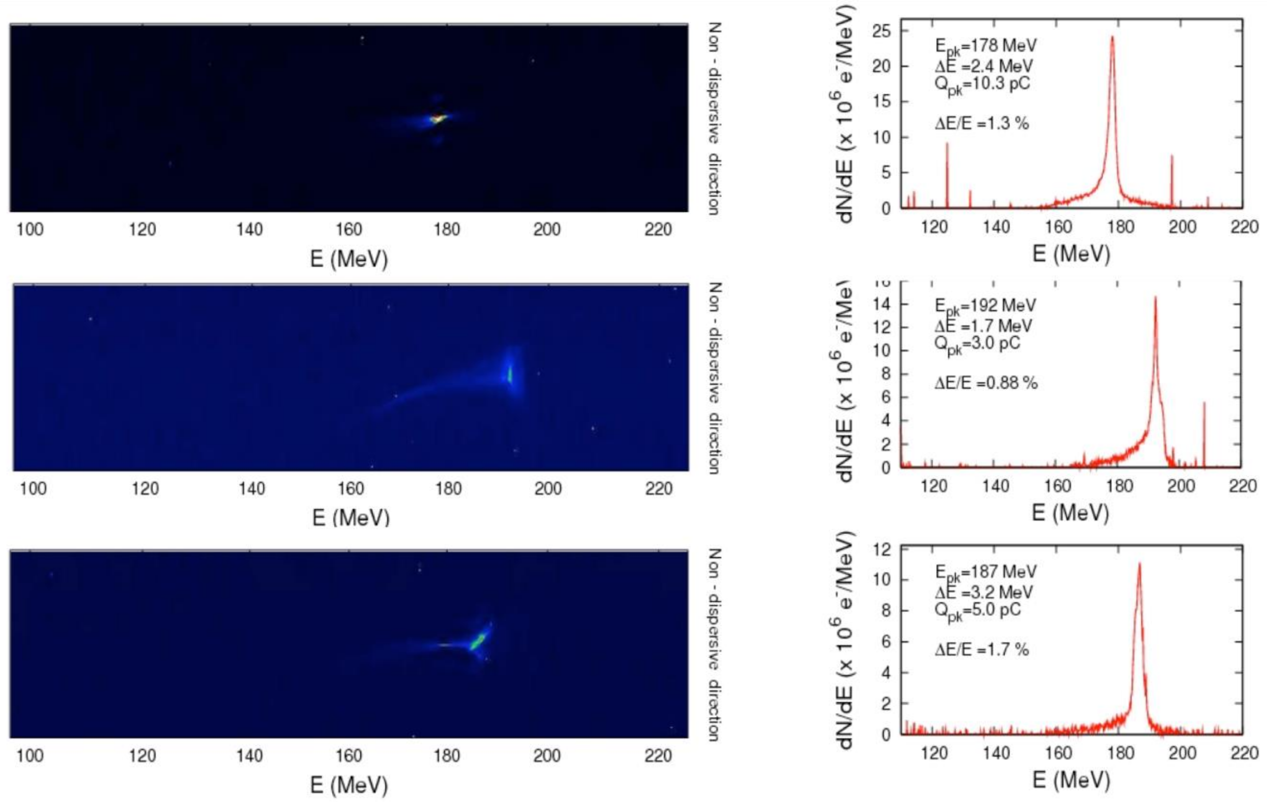
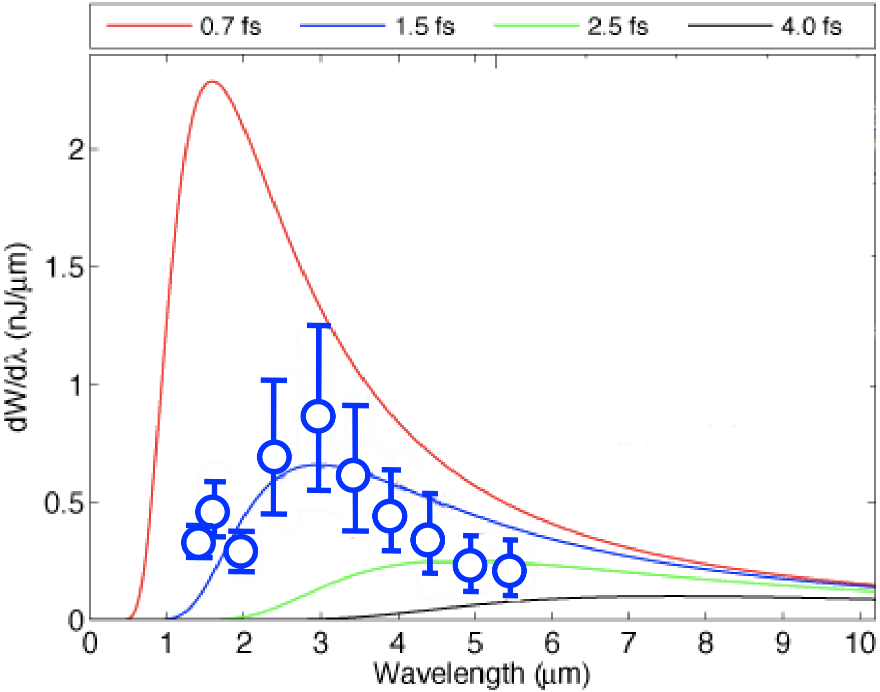
Beam loading effect: 1% energy spread





C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 194804 (2009)

1.5 fs RMS duration: Peak current of 4 kA



Analytic CTR model

Gaussian pulse shape

Measured e-beam :

- Charge
- Energy
- Divergence

Bunch duration

Peak wavelength

Peak intensity

Spectral features

Peak at 3 µm

Coherent

1.5 fs RMS duration : Peak current of 4 kA

O. Lundh *et al.*, Nature Physics, **7** (2011)

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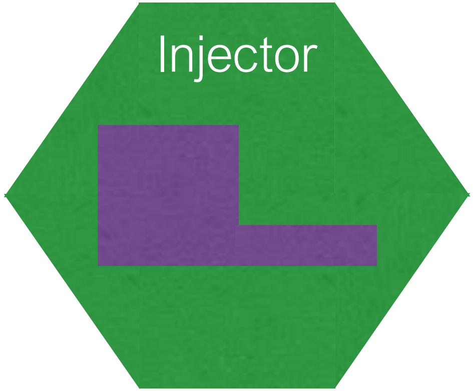
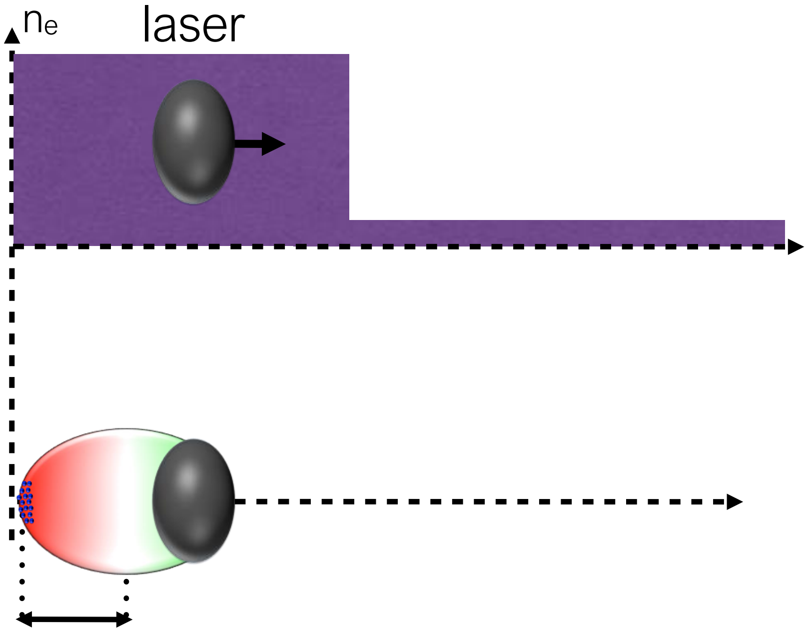
Injector



Injection in a density gradient



Density drop: increase of the cavity lenght which allows injection

Sharp density ramp is requires to localize the injection and reduce the energy spread !

Schmid *et al.*, 2010; Buck *et al.*, 2013

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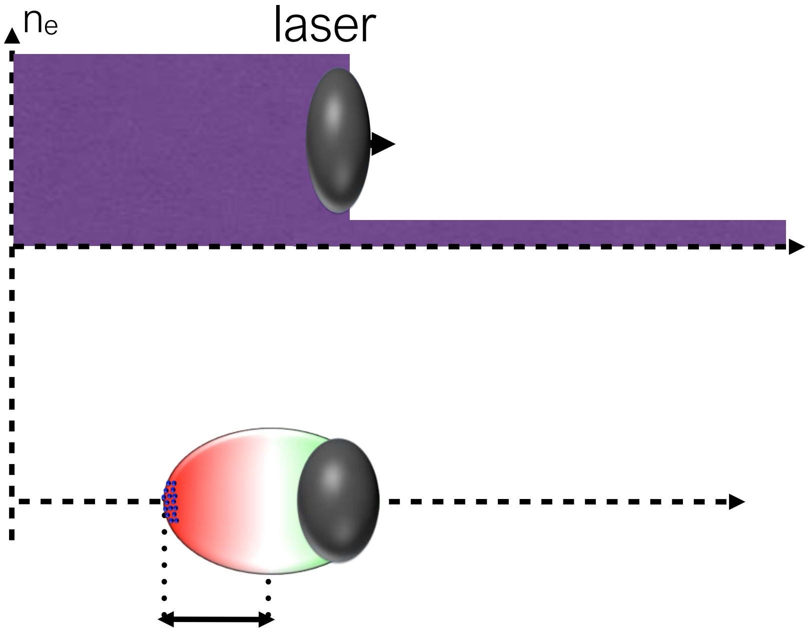
Injection in a density gradient



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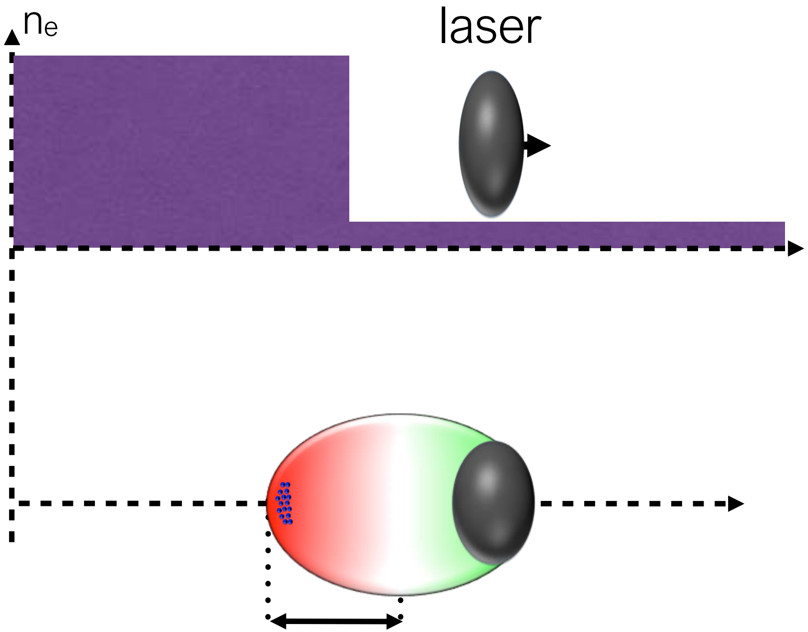

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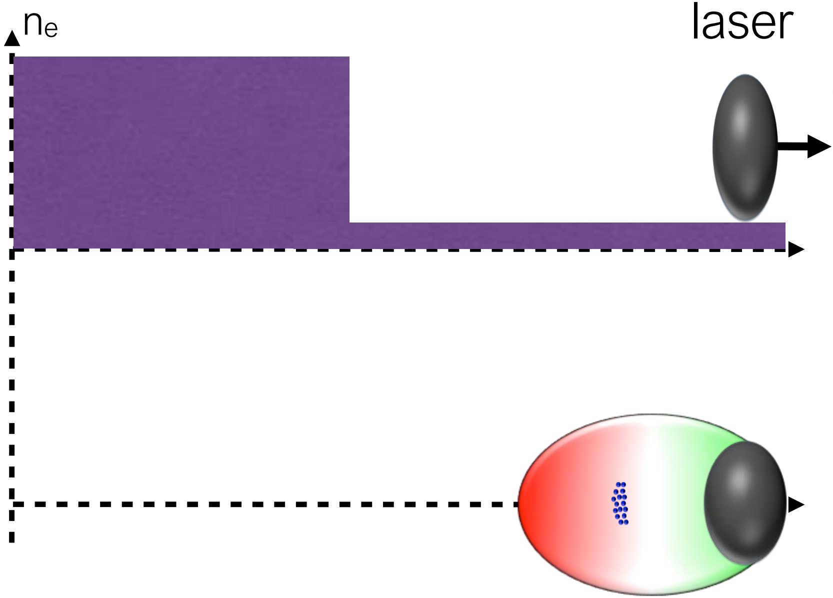

Density drop: increase of the cavity lenght which allows injection

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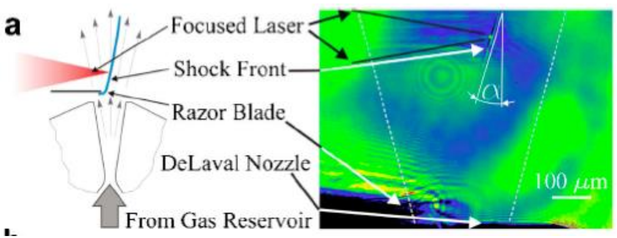
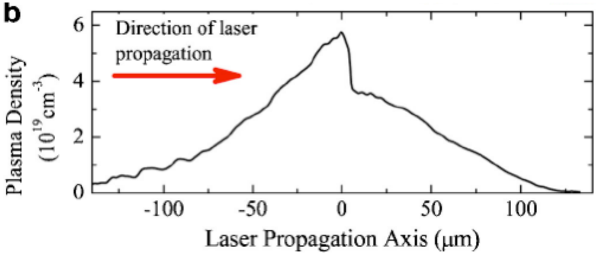
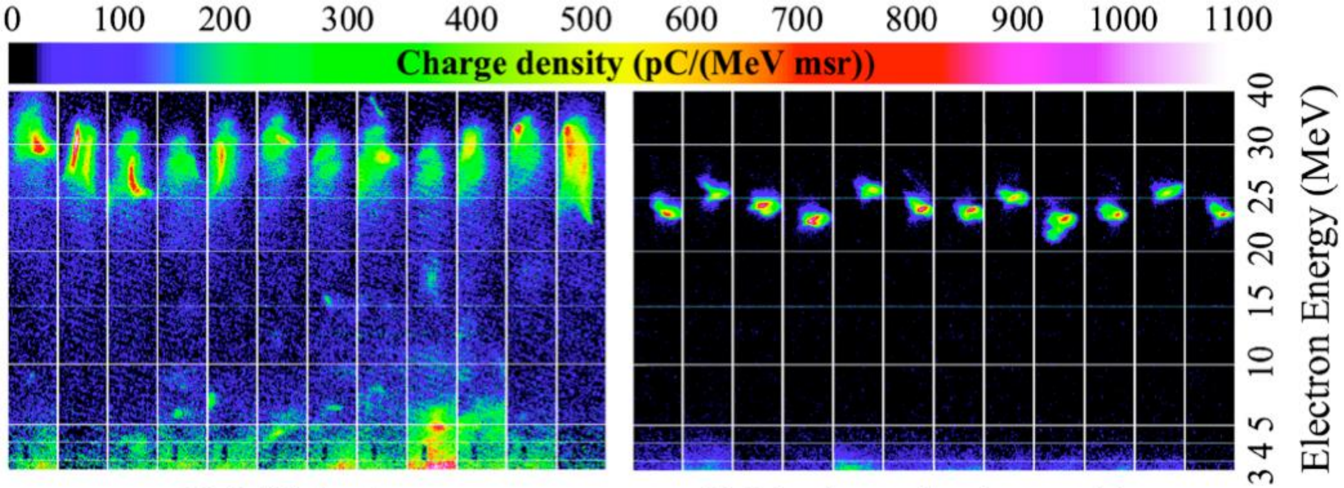


=>





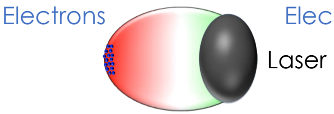
(a) Self injection

(b) Injection at density transition

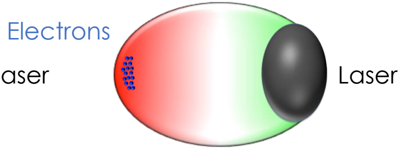
K. Schmid *et al.*, PRSTAB **13**, 091301 (2010)

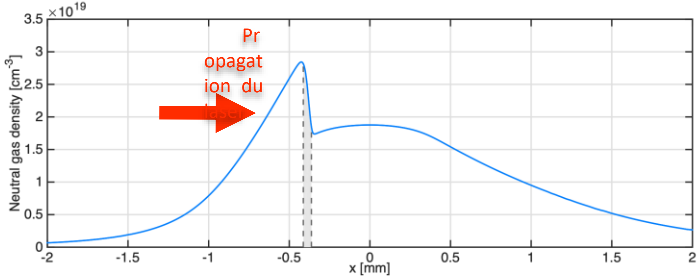
Injection in a density gradient

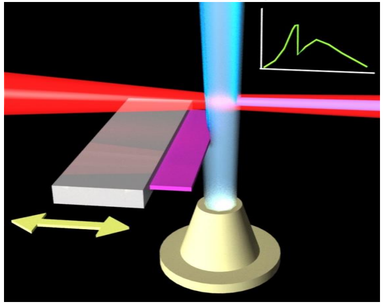
Plasma cavity before the shock front



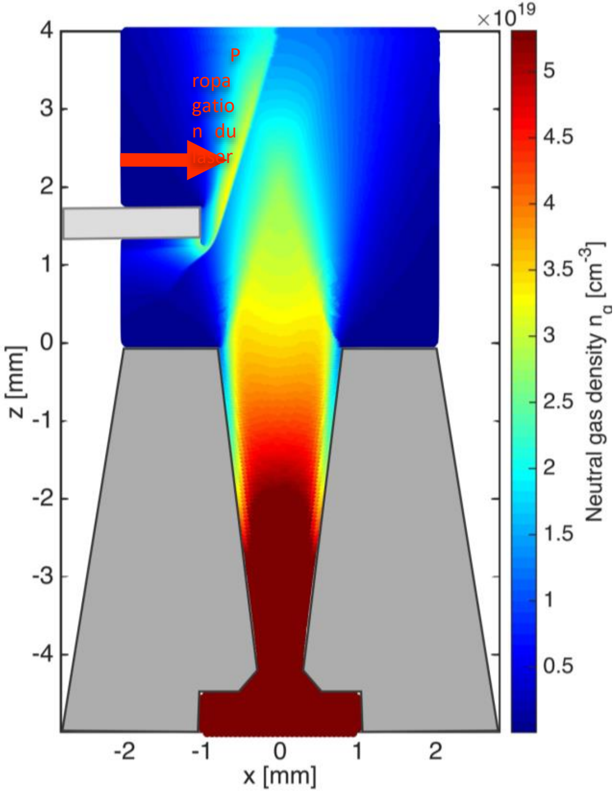
Plasma cavity after the shock front



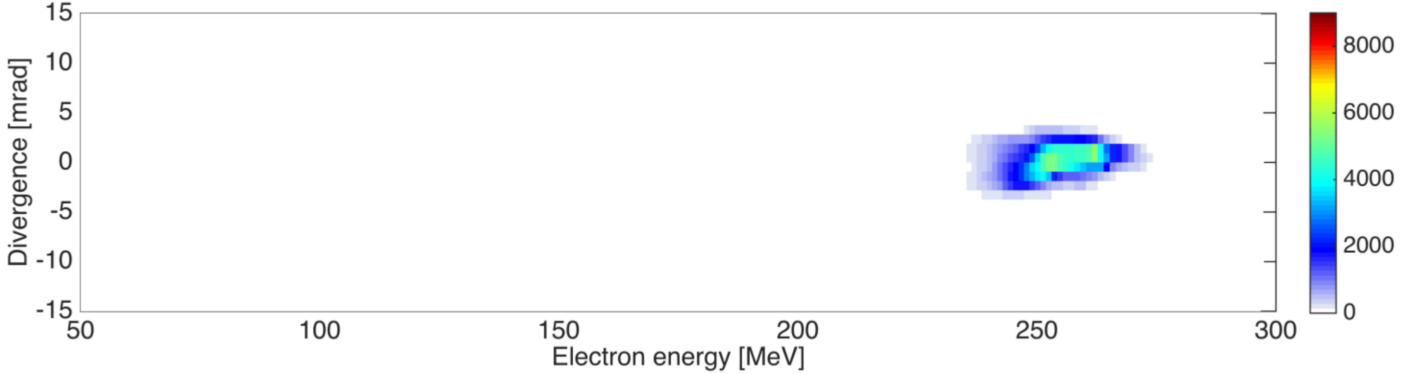




Simulations ANSYS Fluent



Injection in a density gradient



Generation of a stable e-beam ($n_2 = 7.5 \times 10^{18}$ cm^{-3}) :

$$E_{peak} = 256.5 \pm 4 \text{ MeV}$$

$$\Delta E = 15.5 \pm 2 \text{ MeV}$$

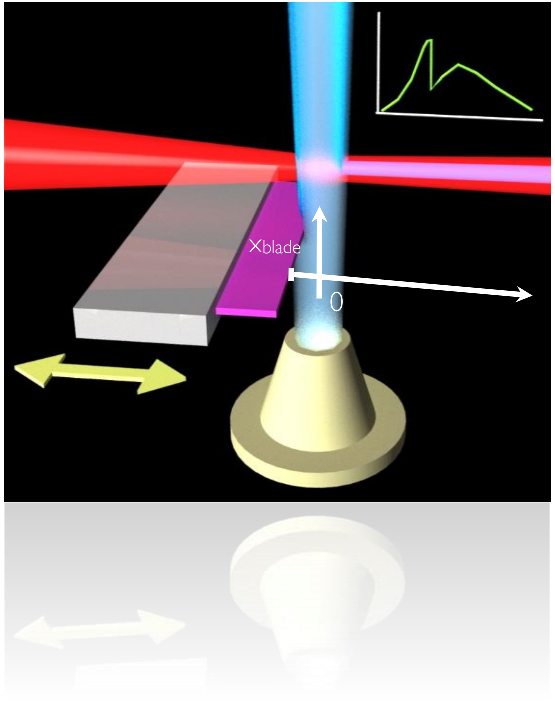
$$\Delta E / E = 6 \pm 1\%$$

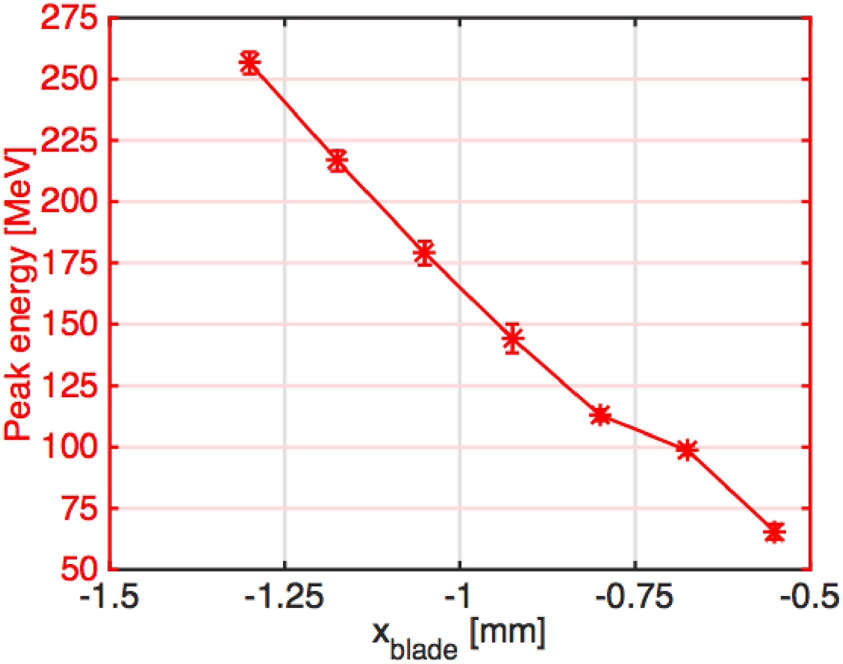
R. Lehe

$$Q_{peak} = 3.2 \pm 0.4 \text{ pC}$$

$$\text{Divergence} = 2.0 \pm 0.3 \text{ mrad}$$

Injection in a density gradient





Electron energies is controlled by the position of the blade

C. Thaury *et al.*, Scientific Reports 5.16310 (2015)

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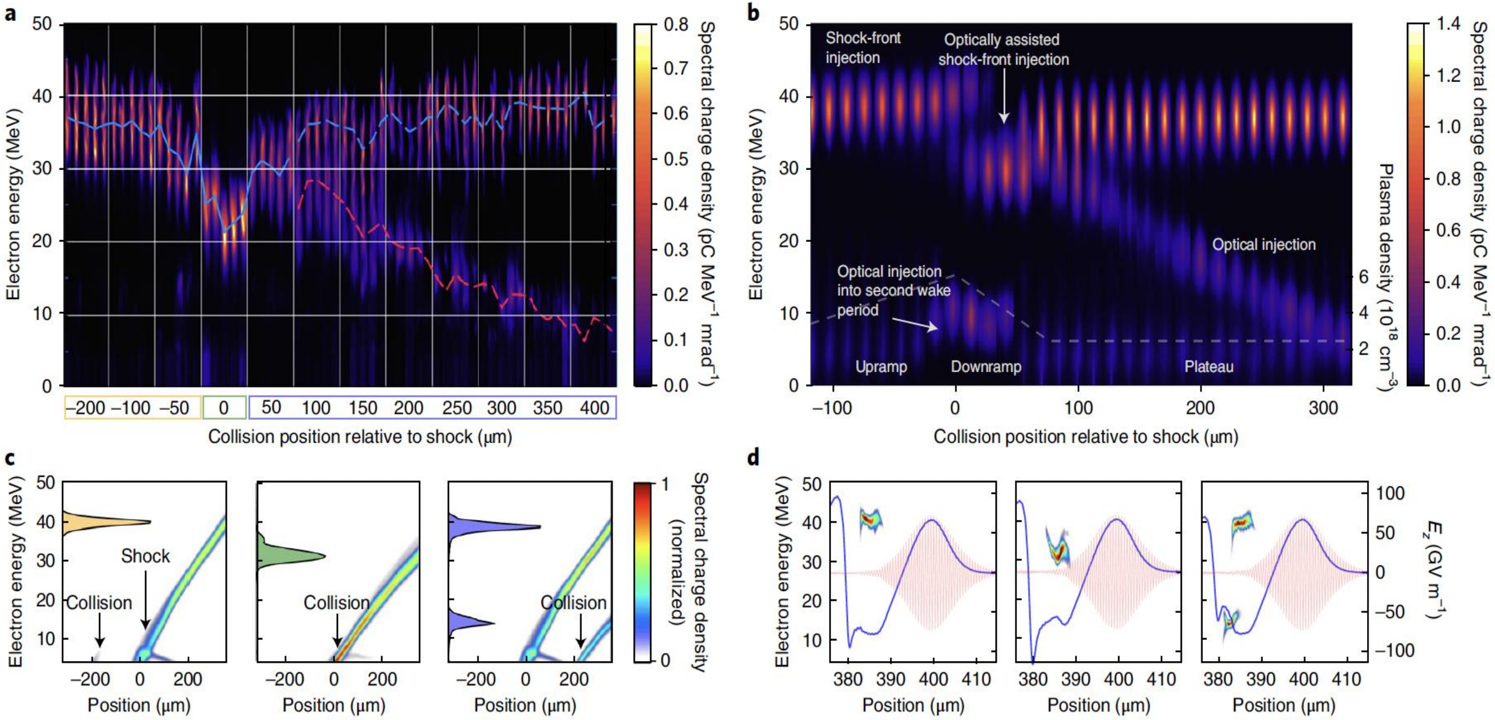
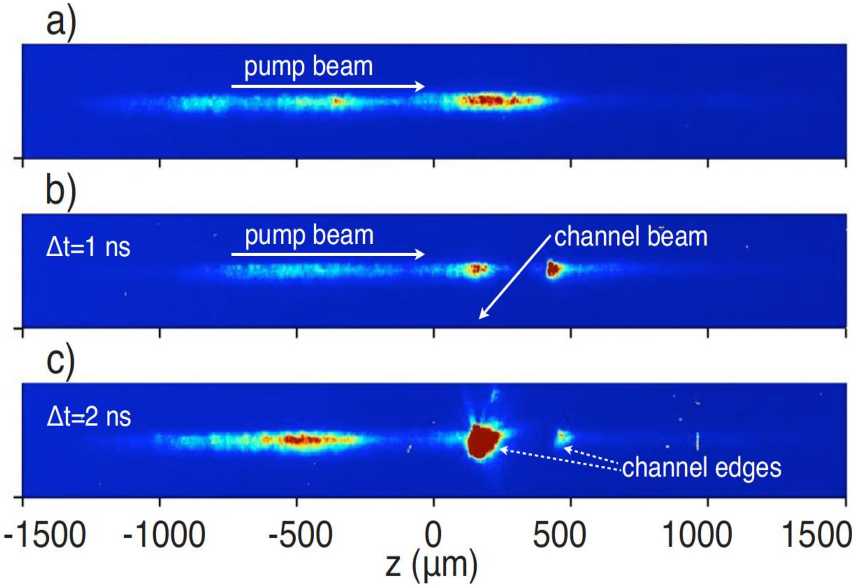
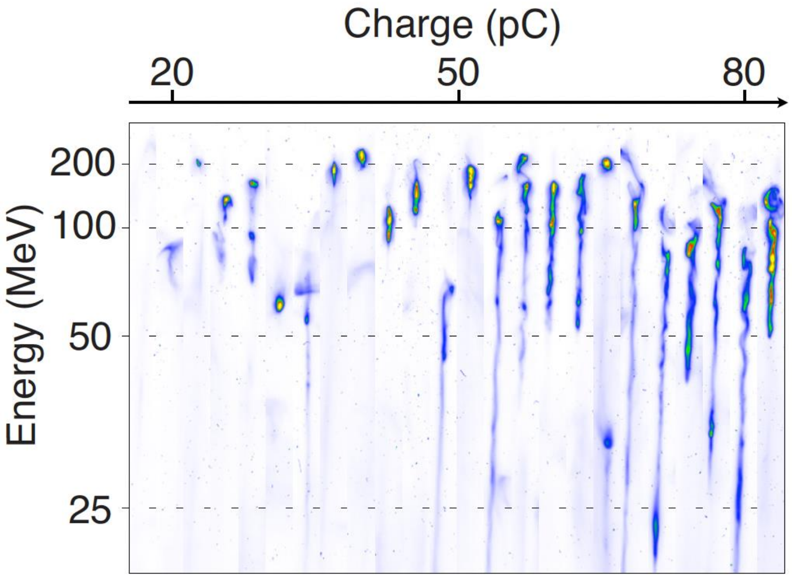
Dual-energy electron beams



J. Wenz *et al.*, Nature Photonics **13** (2019)

Quasi-monoenergetic electron beams using optical shock injection

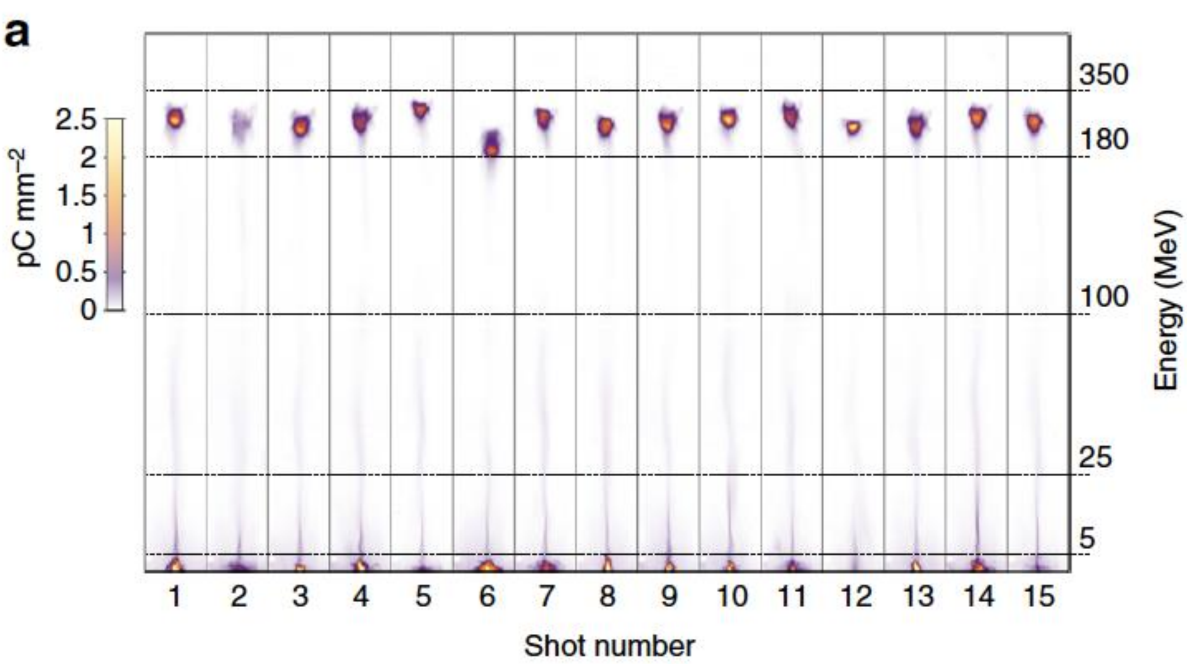




Optical shock injection at LOA, $n_e=10^{19}$ cm^{-3}, t=2 ns, and $I_l=1.5\text{x}10^{17}$ W/cm^2

J. Faure *et al.*, PoP **17,** 083107 (2010)

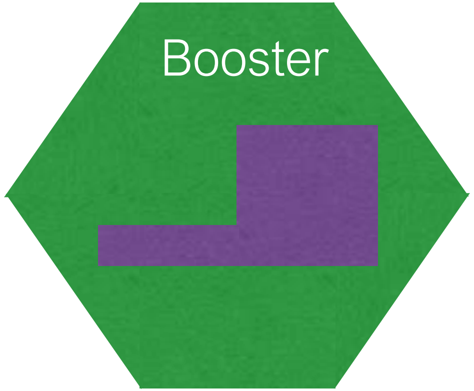
Self Truncated ionization injection: highest charge



Energy spectra of 15 consecutive shots. Obtained with 1.6 mm-long plasma at 3.1×10^{18} cm^{-3}, 1% nitrogen doping and 2.5J/30fs laser

J. P. Couperus *et al.*, Nature Comm. **8**, 487 (2017)

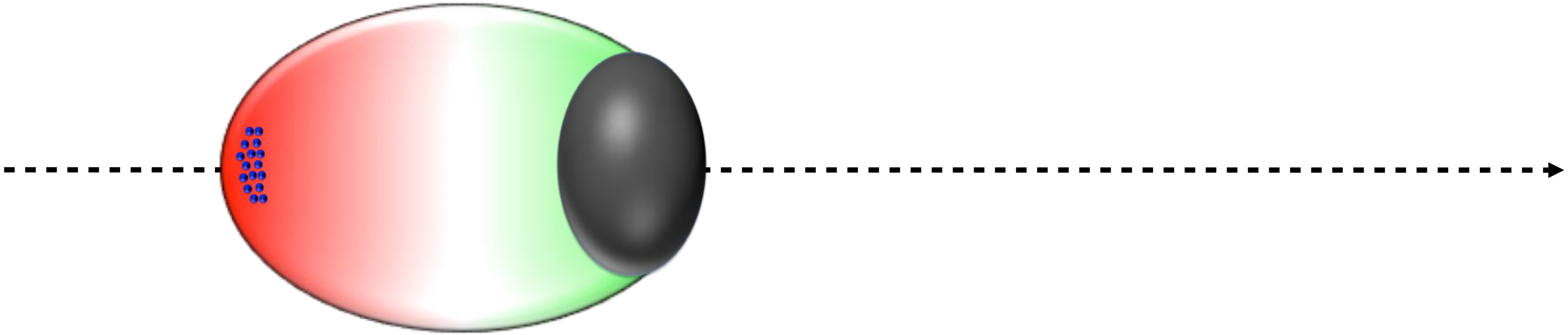
Booster



Booster

Since the laser group velocity is < c, when electrons energy is getting ~c they dephase

→ electrons reach the center of the cavity and start to be deccelerated



R. Lehe

Overcoming the dephasing limit

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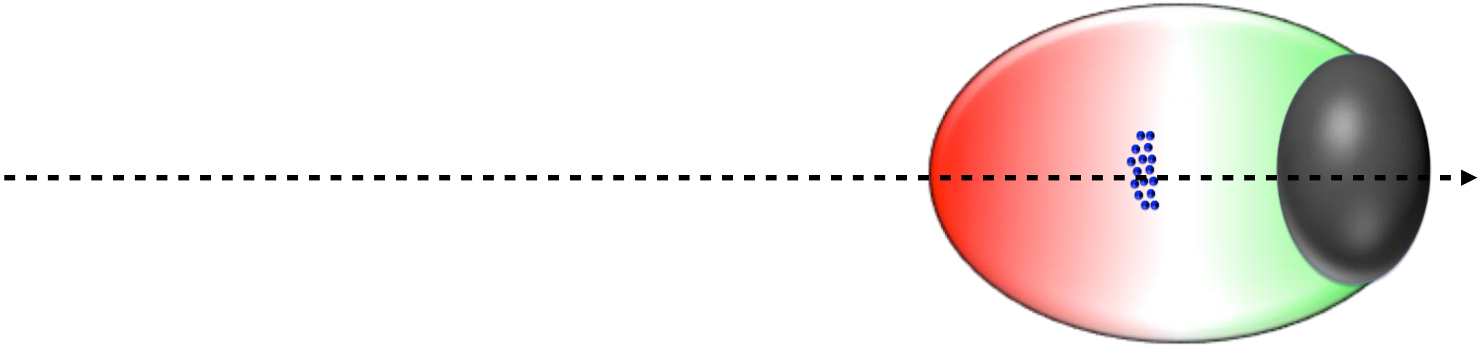
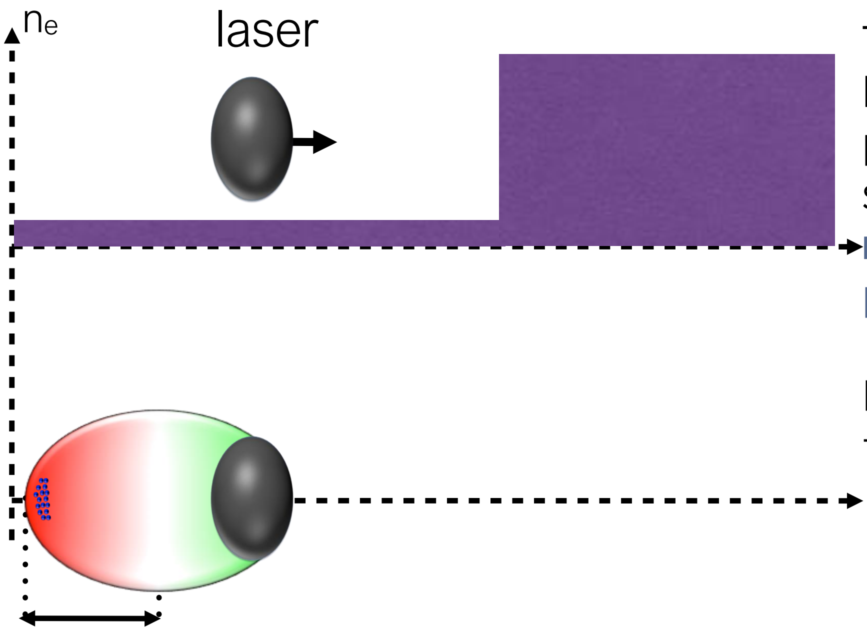


R. Lehe

Overcoming the dephasing limit



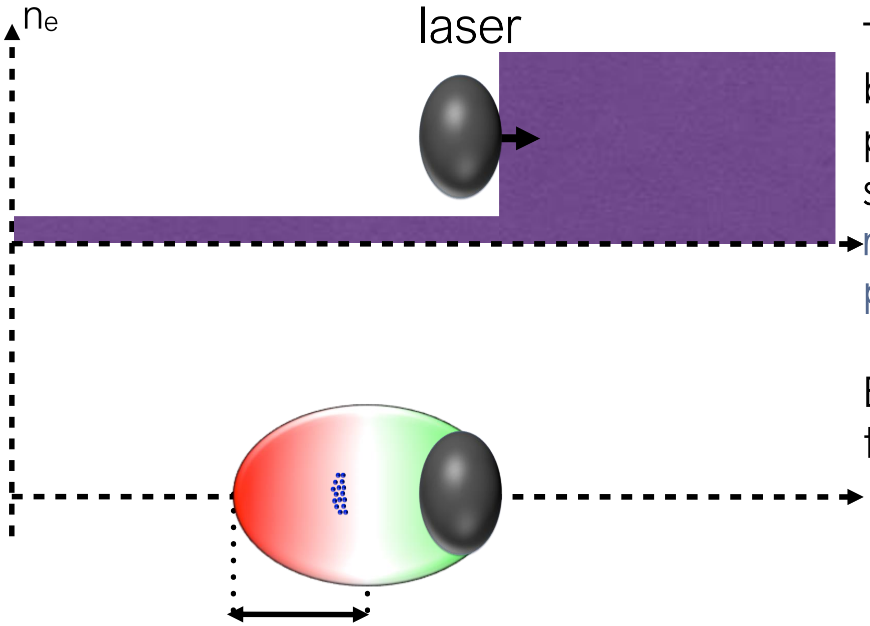
The reduction of the bubble size at the right position by increasing suddenly the density resets the electrons phase.

Electrons can start again to gain energy.

R. Lehe

Katsouleas *et al.*, 1986; Sprangle *et al.*, 2001

Overcoming the dephasing limit



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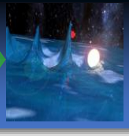

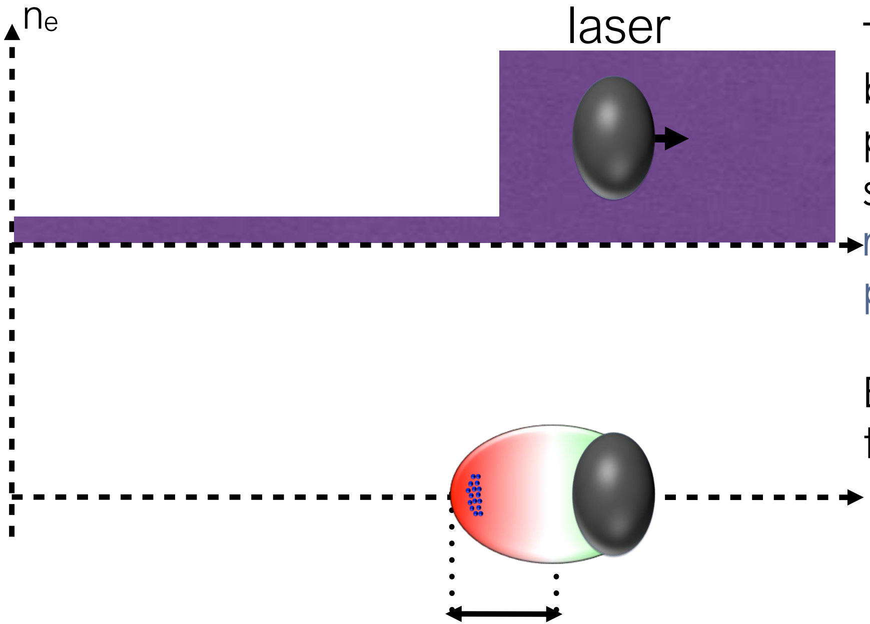

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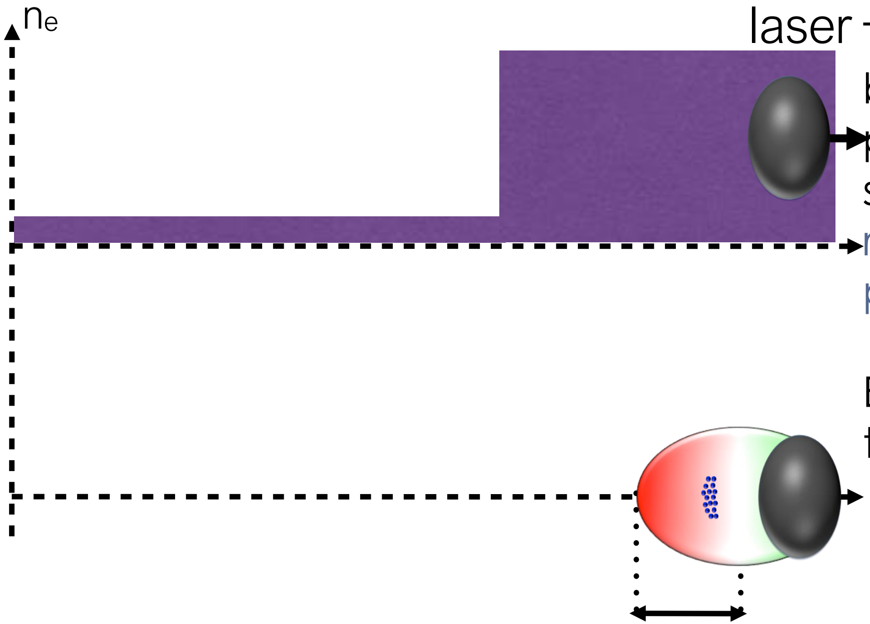

The reduction of the bubble size at the right position by increasing suddently the density resets the electrons phase.

Electrons can start again to gain energy.

R. Lehe

R. Lehe

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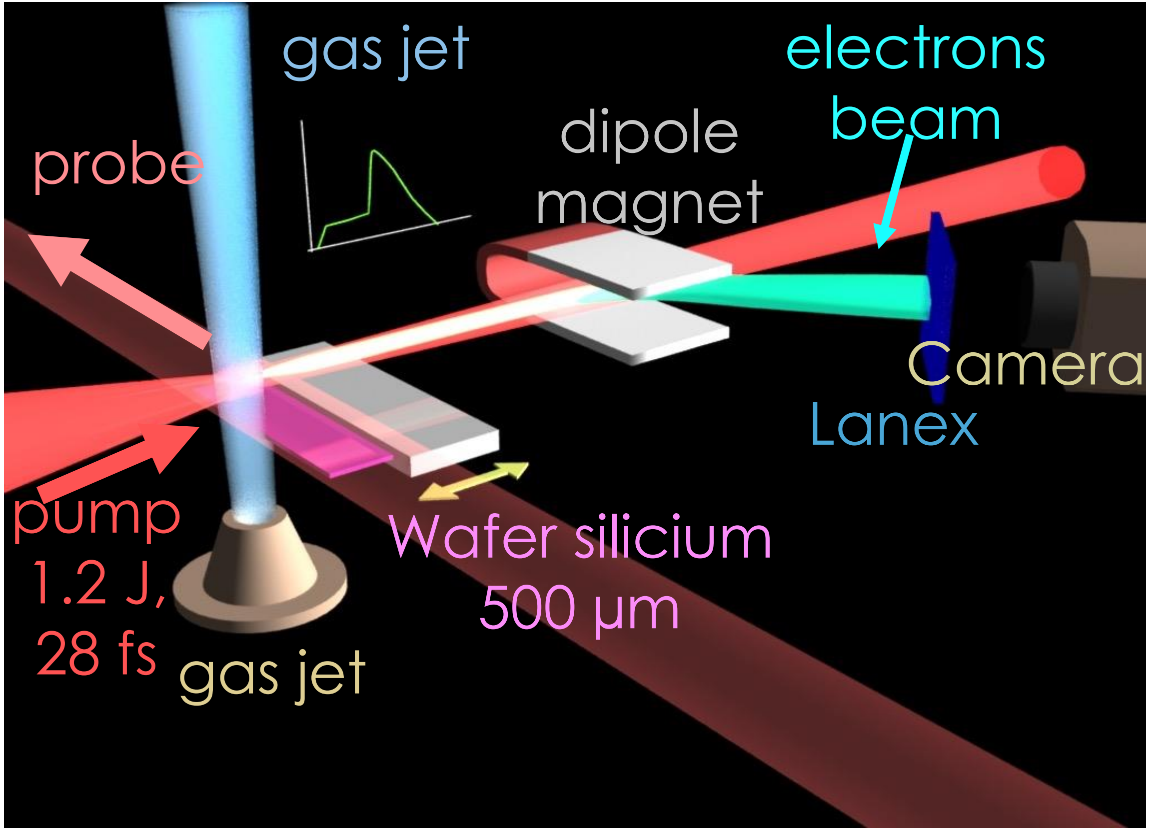
Experimental set-up



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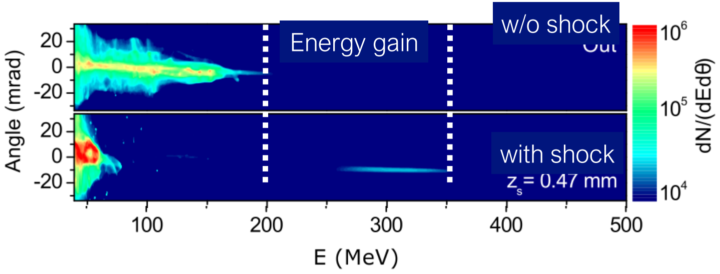
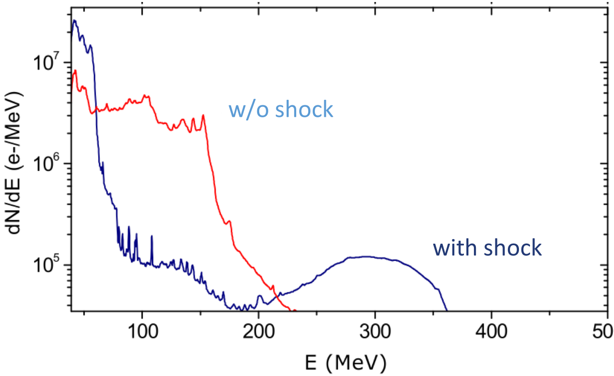
Longitudinal phase space manipulation

Experimental results

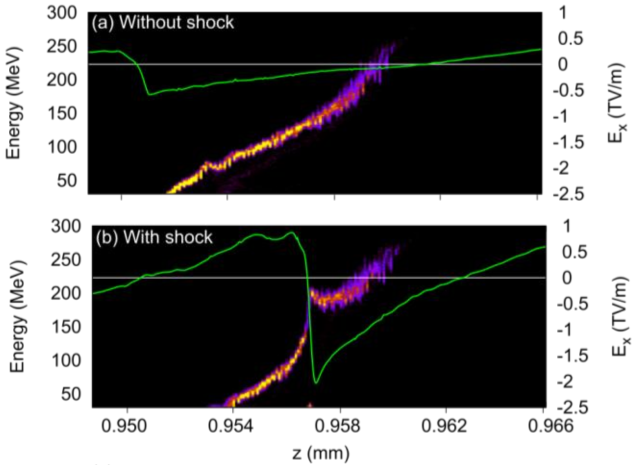
2D dispersion corrected spectra

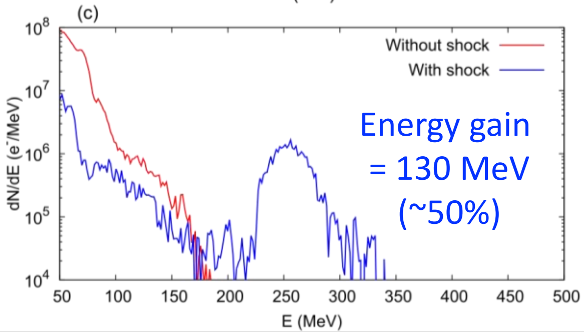


Angularly integrated spectra



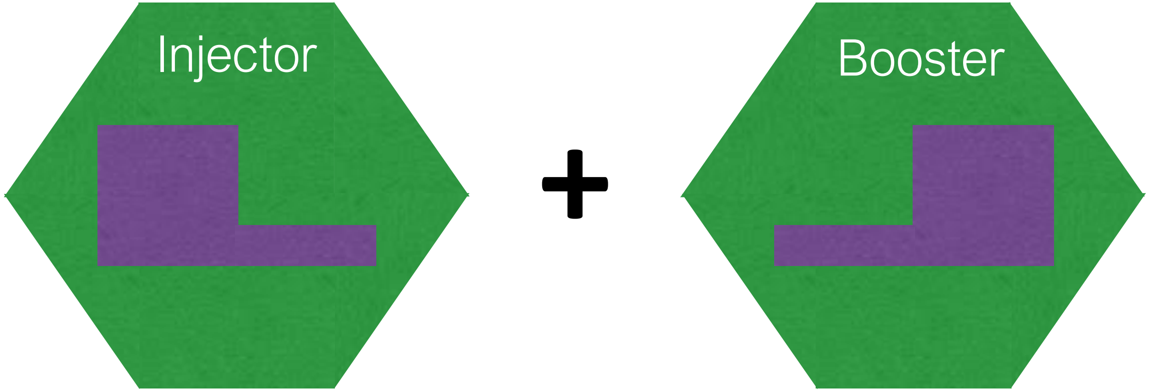
Calder-Circ PIC Simulations





Energy gain
= 130 MeV
(~50%)

Combining Injector and Booster



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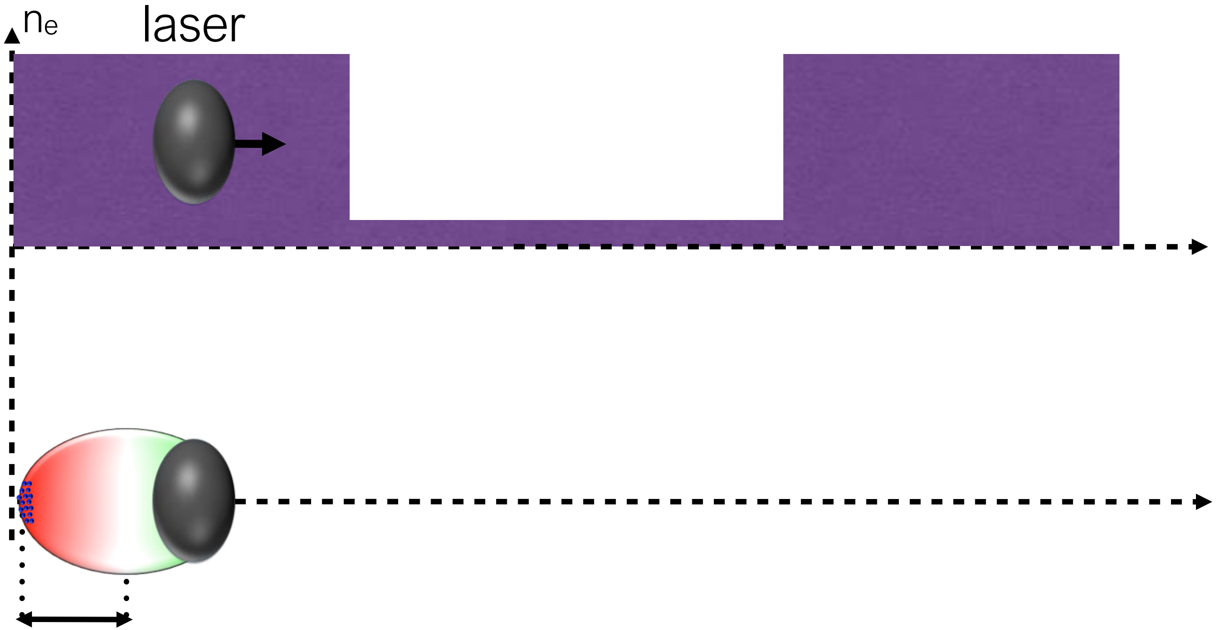

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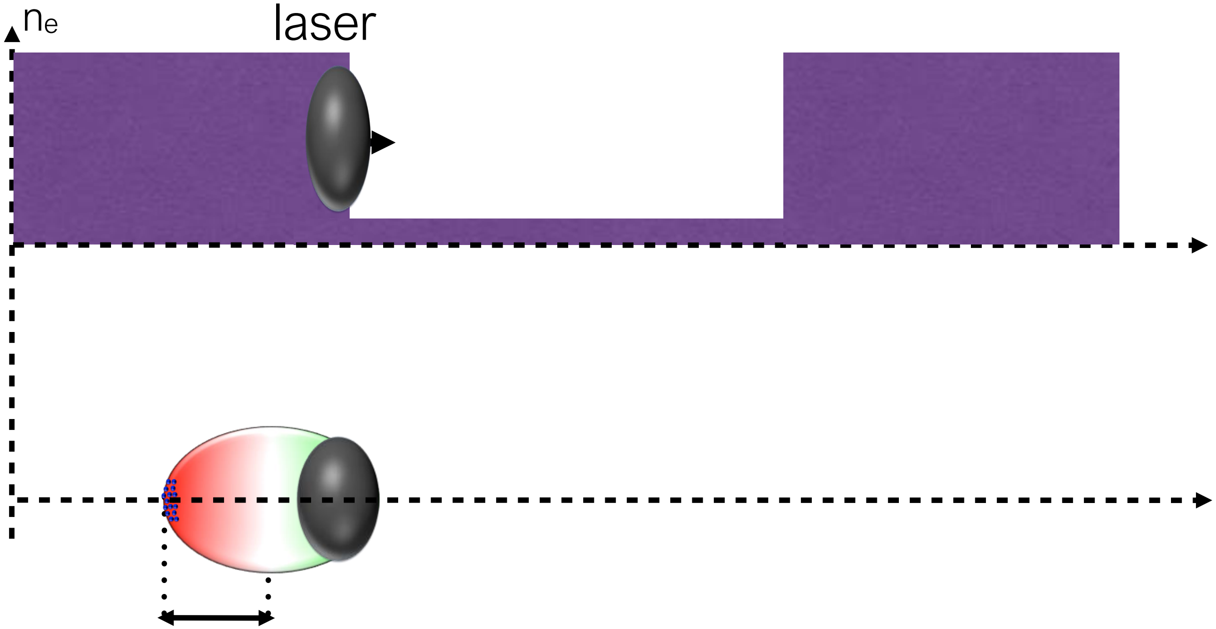

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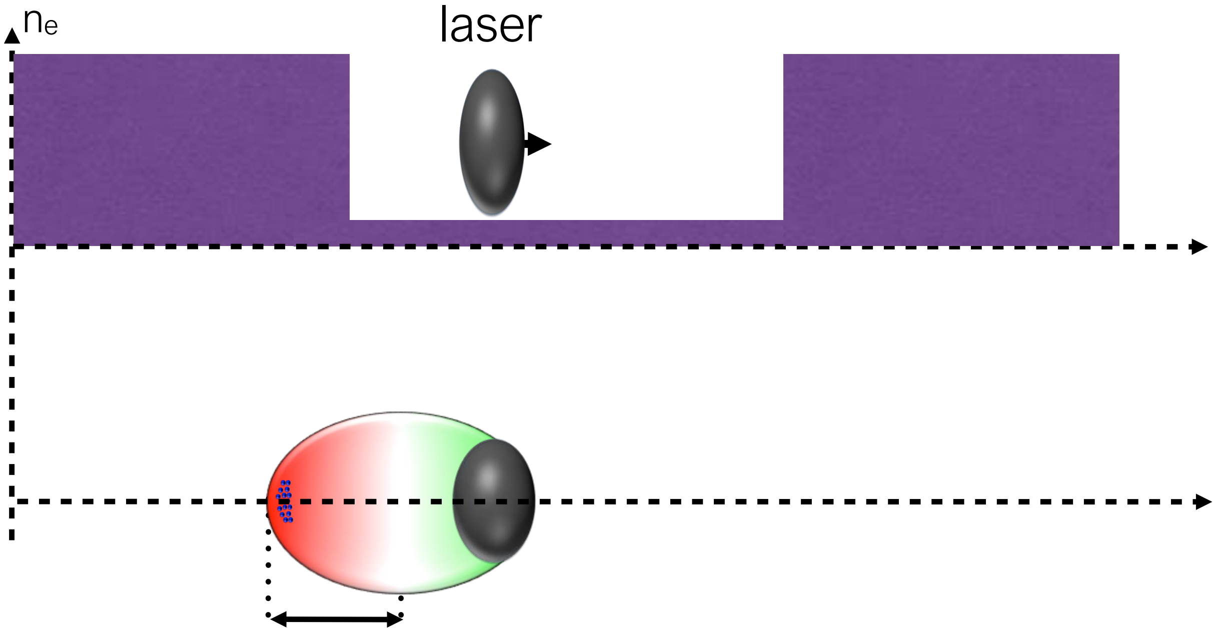

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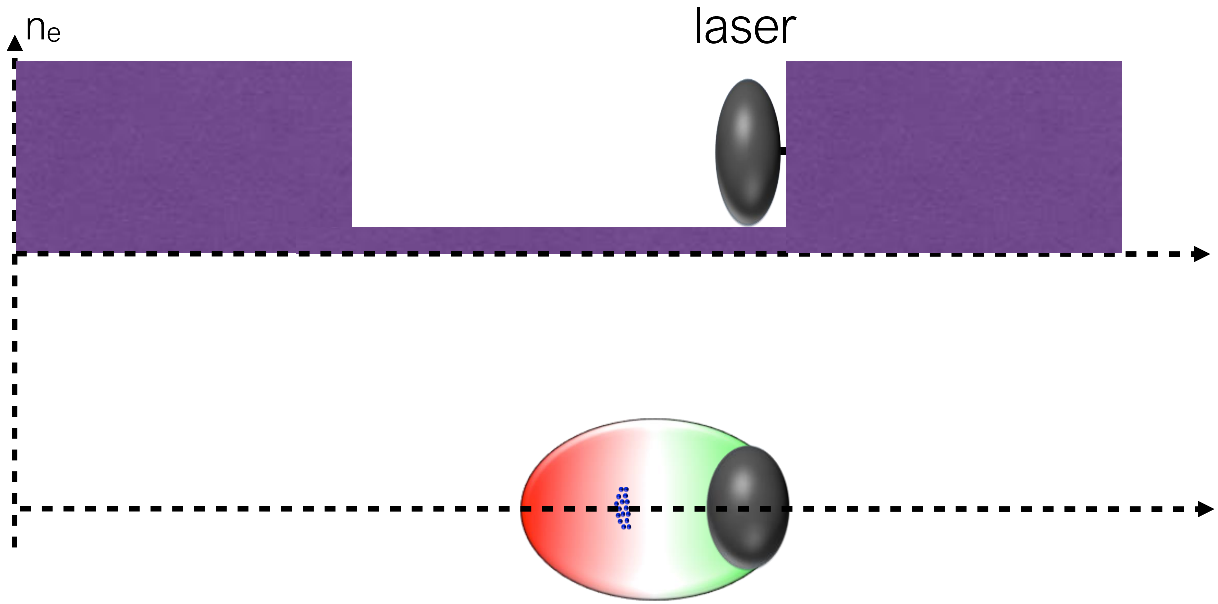

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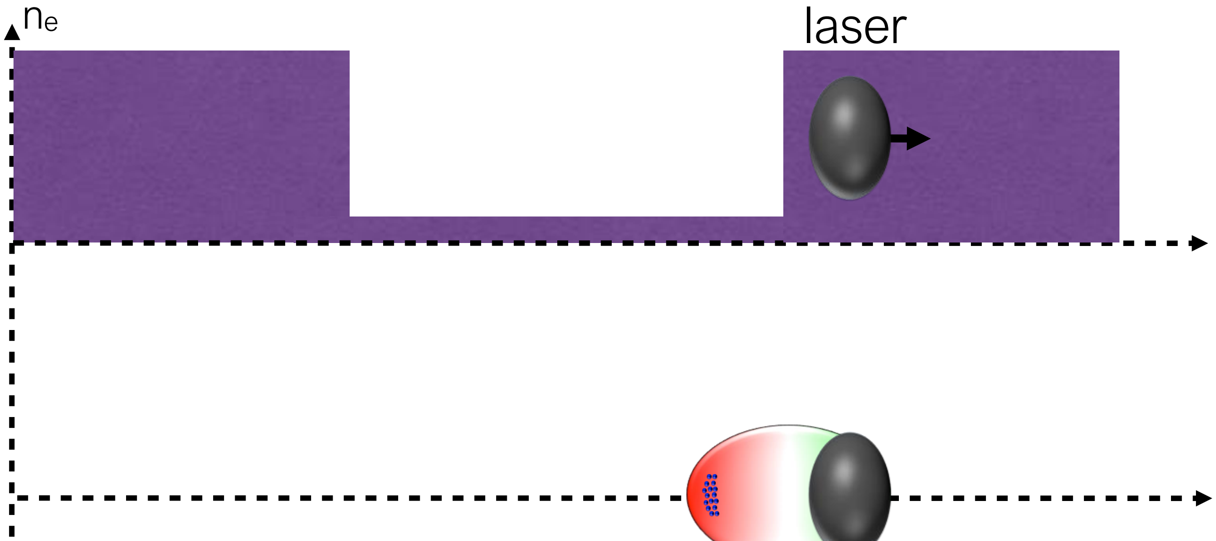

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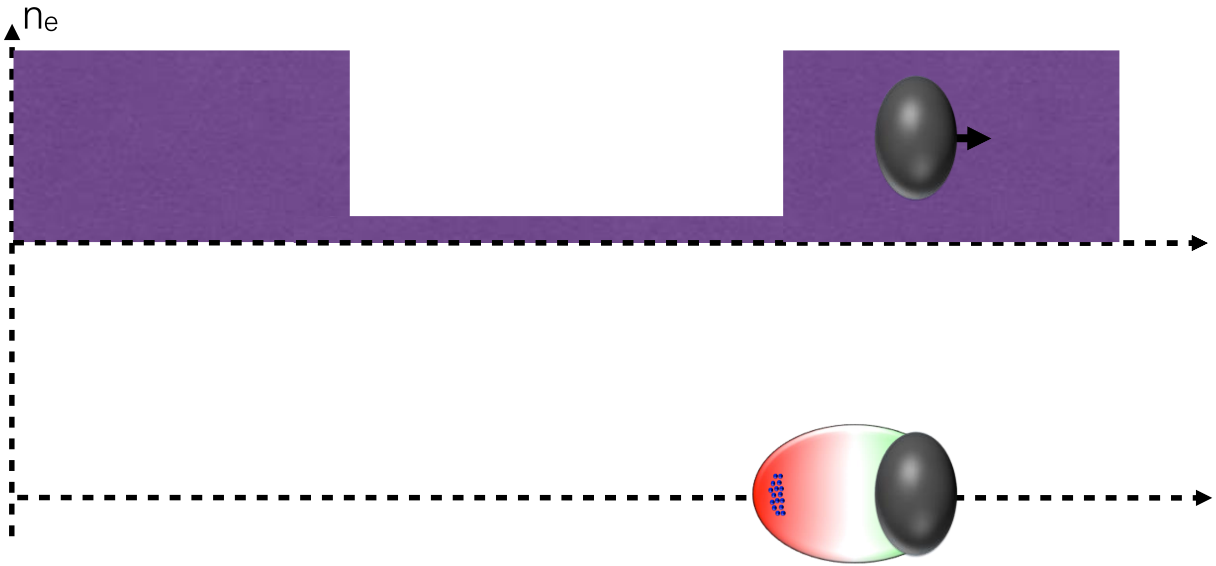

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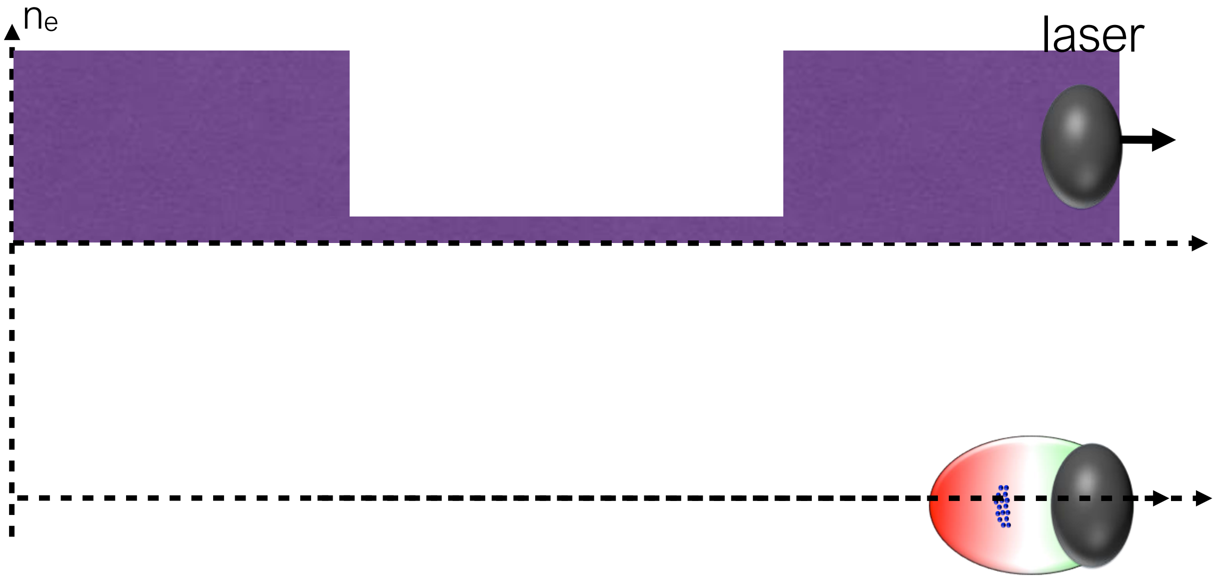

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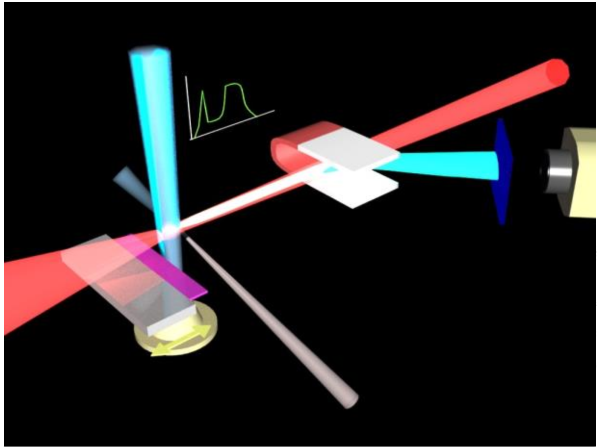
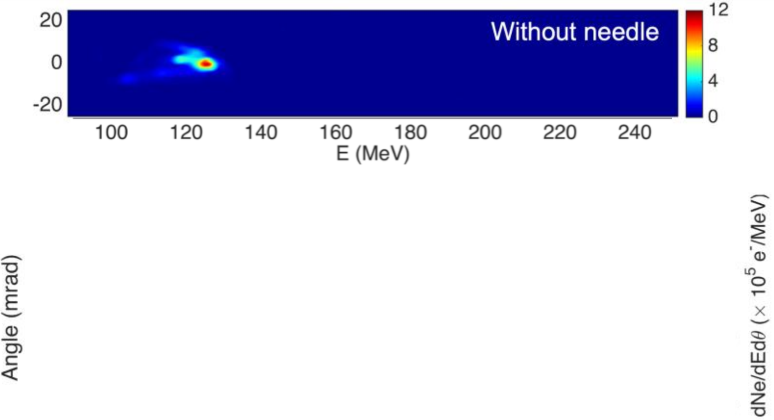


boosting a monoenergetic electron beam



E. Guillaume *et al.*, PRL **115** (2015)

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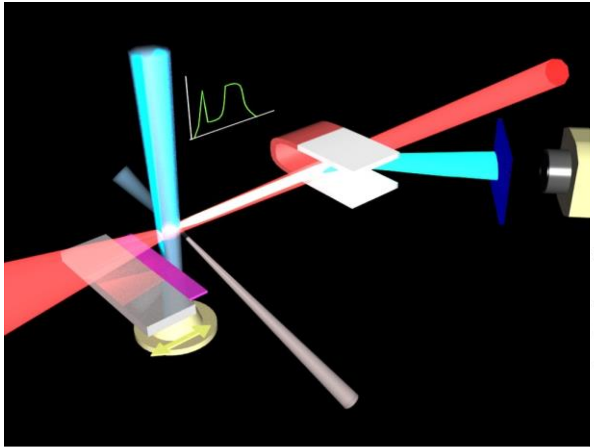
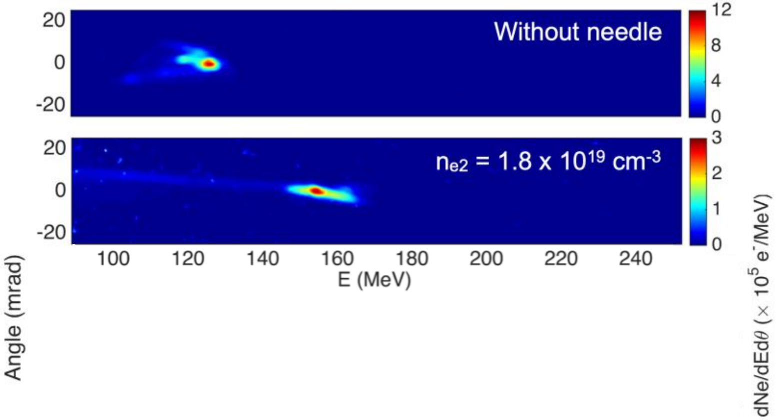
Energy booster

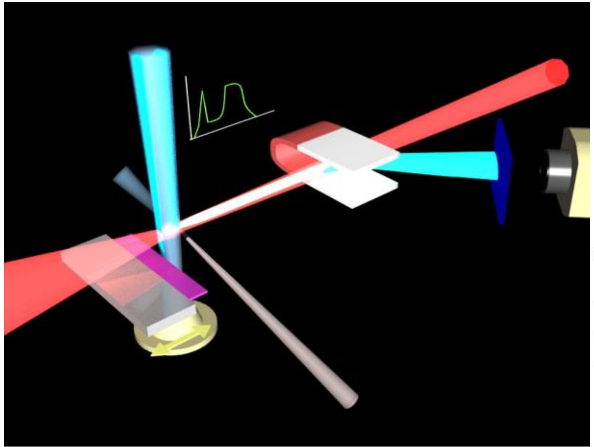


boosting a monoenergetic electron beam

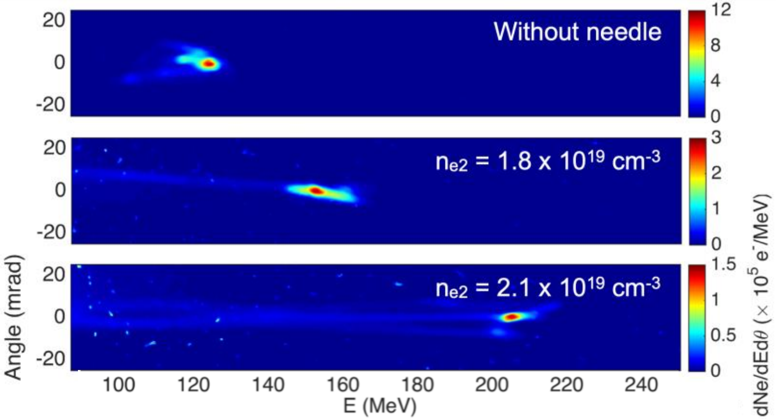


E. Guillaume *et al.*, PRL **115** (2015)

Combining Injector and Booster

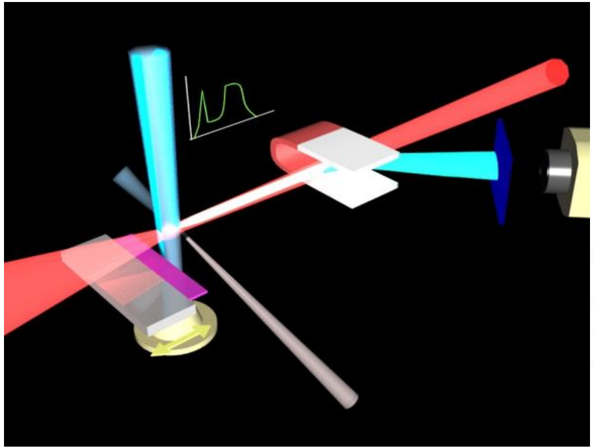


boosting a monoenergetic electron beam

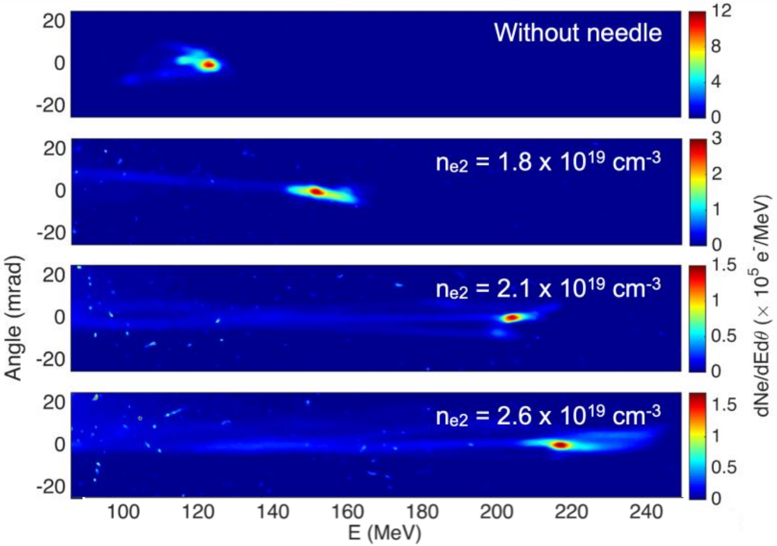


E. Guillaume *et al.*, PRL **115** (2015)

Combining Injector and Booster

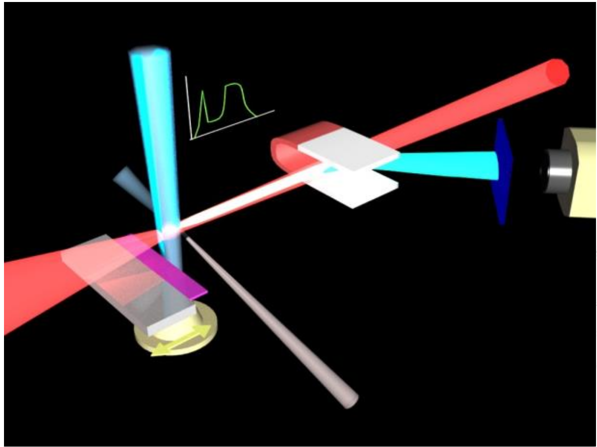


boosting a monoenergetic electron beam

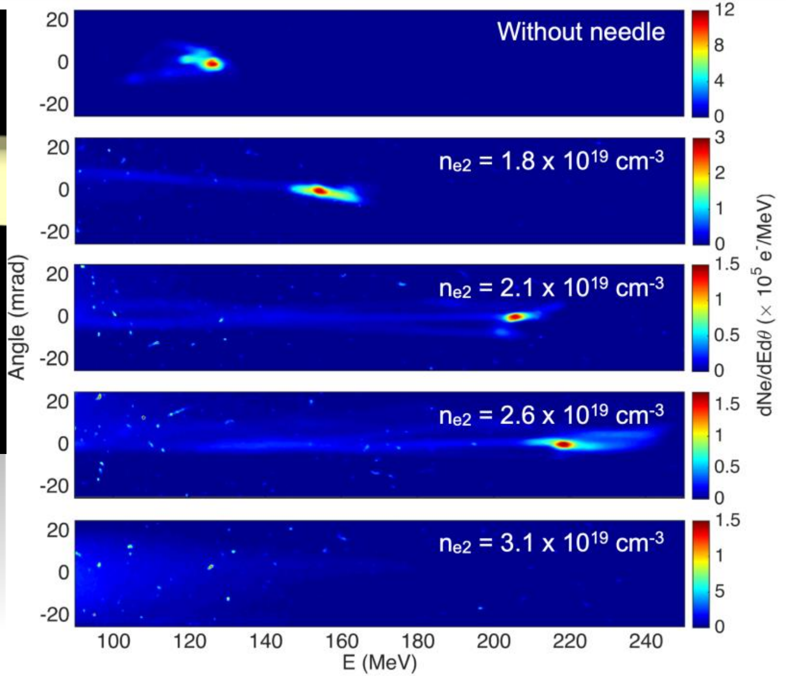


E. Guillaume *et al.*, PRL **115** (2015)

Combining Injector and Booster



boosting a monoenergetic electron beam



E. Guillaume *et al.*, PRL **115** (2015)
A. Döpp *et al.*, PoP **23** 056702 (2016)

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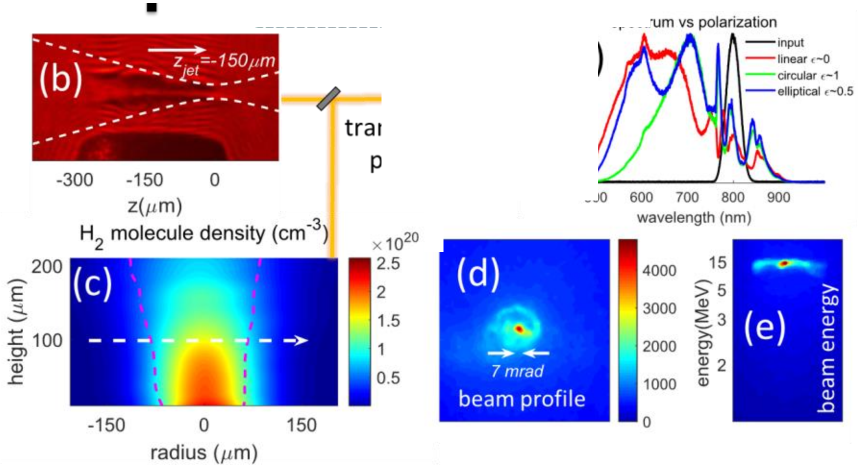
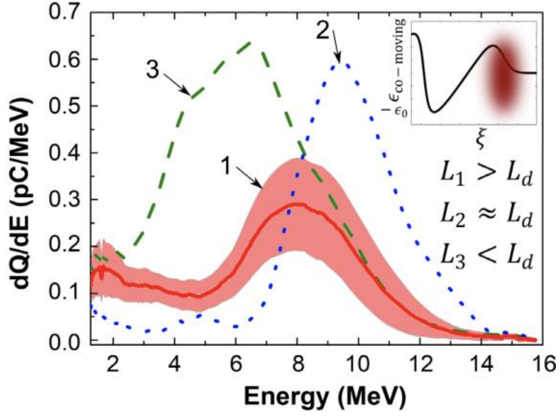
15 MeV QM e^- beam with kHz-mJ laser



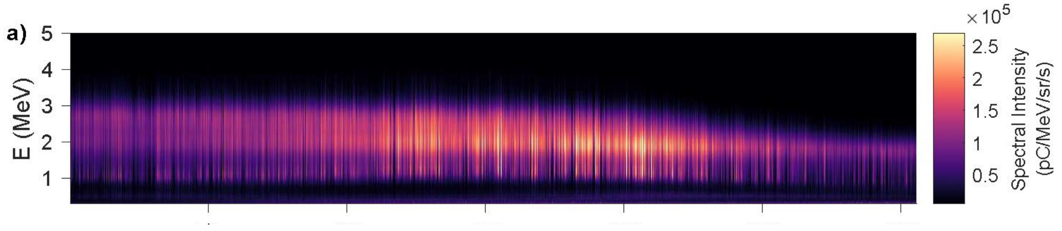
electron beam @ 15 MeV produced at 1-kHz repetition rate
2.5-pC charge with <7-mrad beam divergence
5-fs - 2.7 mJ laser incident
Thin, near-critical-density hydrogen gas jet.
(from Milchberg group)



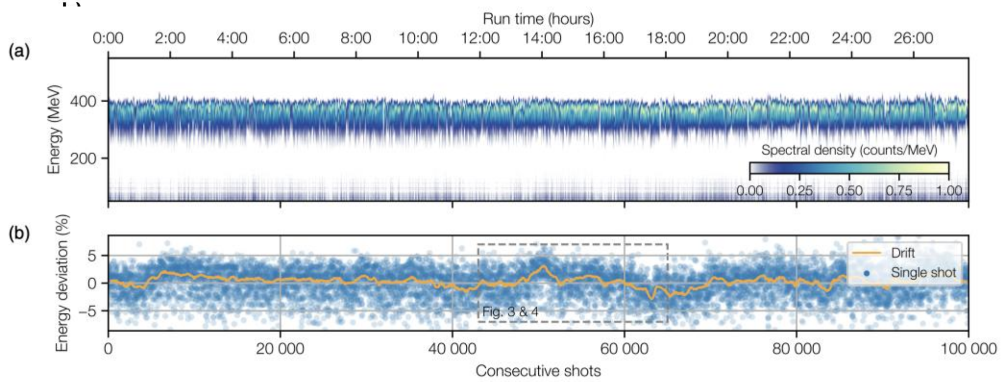
Average electron spectrum over 20 shots
And two typical single-shot electron spectra
(for L2 and L3)
at 7.7 x10^{19} cm^{-3} and <5-fs LWS-20 pulses
(from L. Veisz group)

F. Salehi *al.*, Phys. Rev. X 11, 021055 (2021)   D. E. Cardenas *al.*, Phys. Rev. AB 23 (2020)

Stable & continuous operation



kHz-mJ- 5fs
laser system
at LOA
(France)

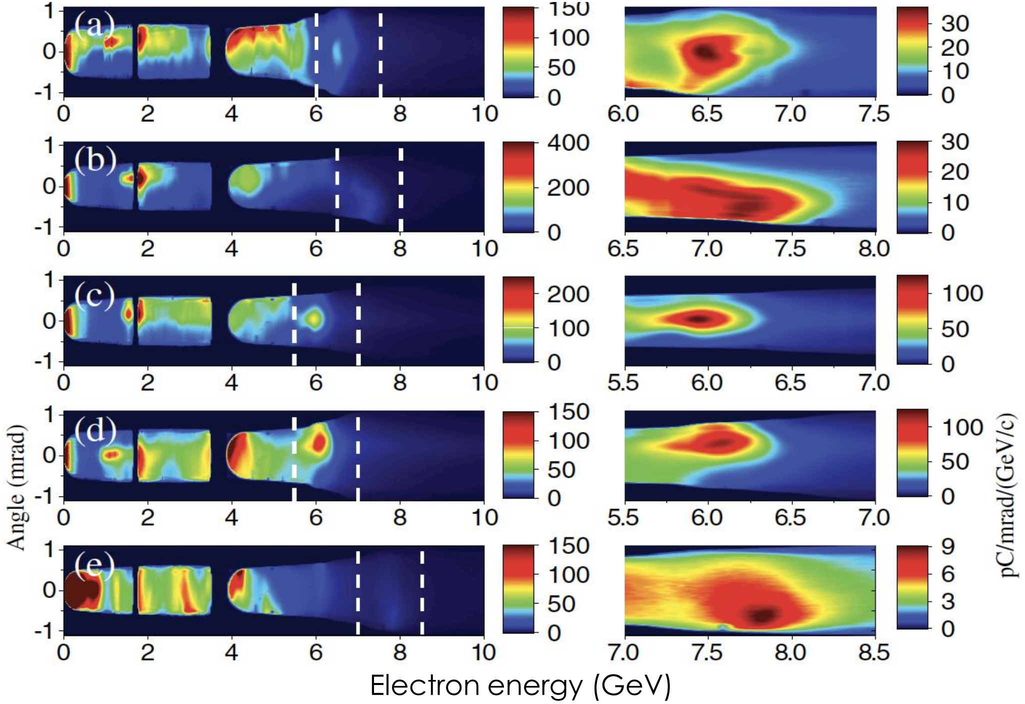


1 Hz - 3J 40 fs
laser system at
DESI
(Germany)

A. R. Maier *et al.*, Phys. Rev. X **10**, 031039 (2020), L. Rovige *et al.*, Phys. Plasmas **28**, 3 (2021)

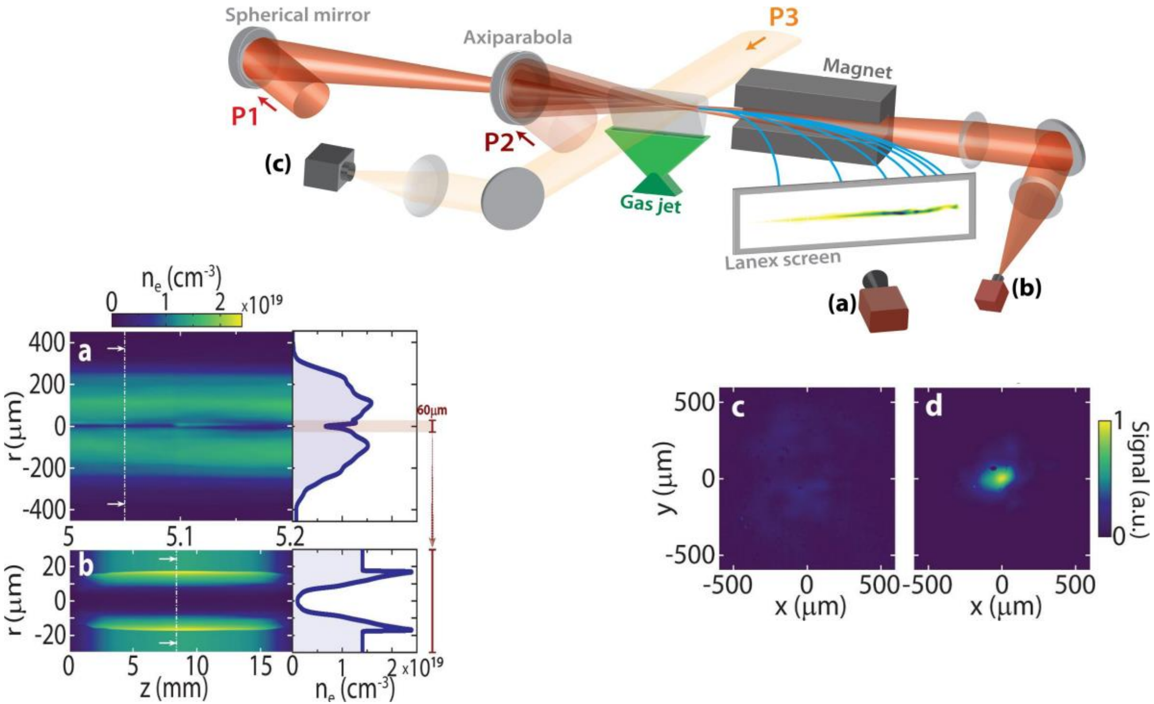
8 GeV energy gain in 20 cm @ LBNL

Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide



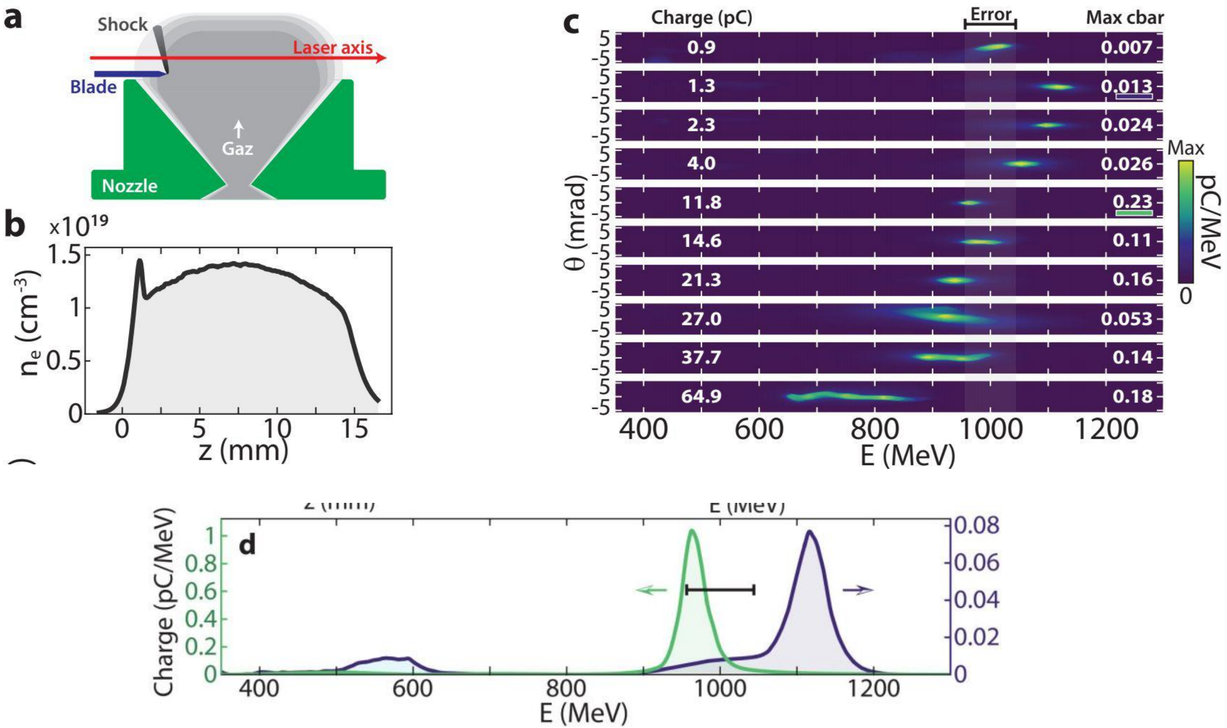
A. J. Gonsalves *et al.*, PRL **122**, 084801 (2019)

Acceleration in a laser generated waveguide



K. Oubrerie *et al.*, Light Sci. & Appl. **11**, 180 (2022)

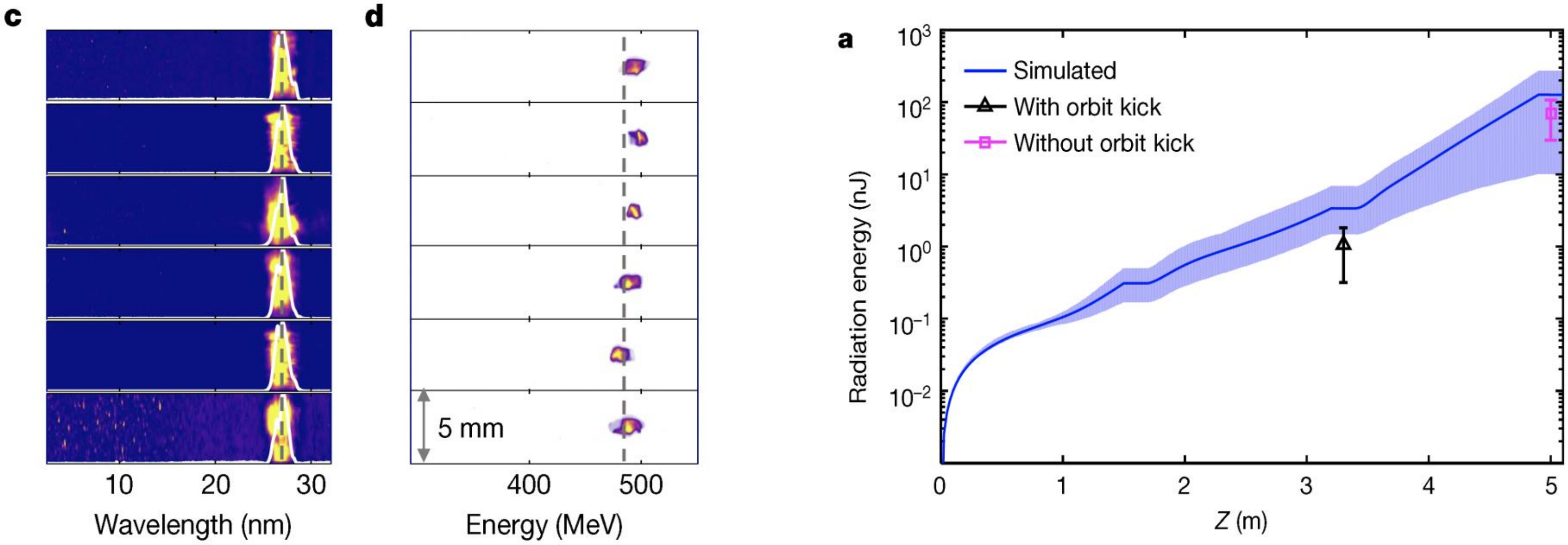
Controlled injection in a plasma waveguide



Quasi Mono energetic electron beam @ more than GeV with 50 TW laser with few pC

K. Oubrerie *et al.*, Light Sci. & Appl. **11**, 180 (2022)

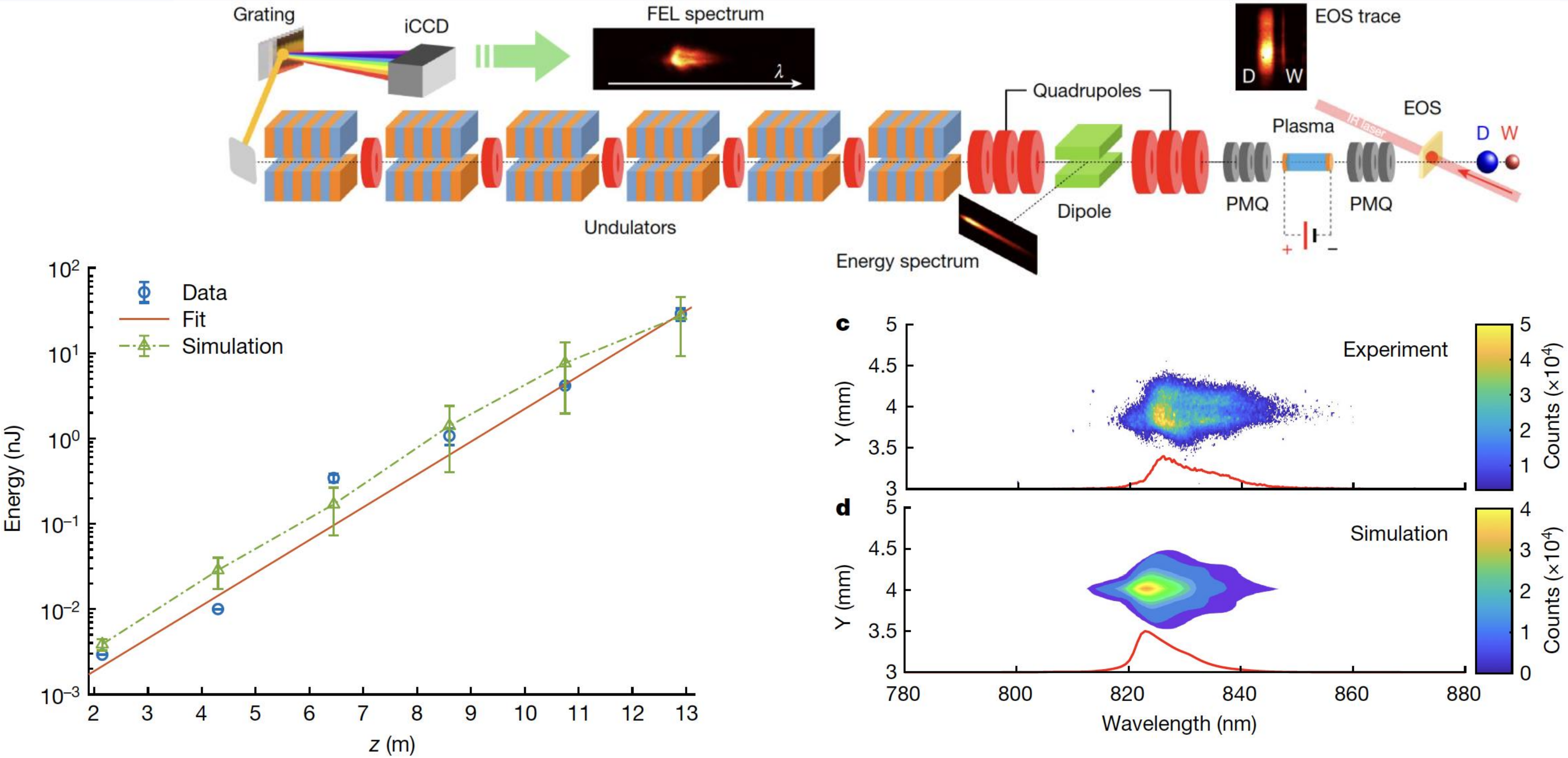
Free-electron lasing at 27 nanometres based on a LWFA



200-TW laser system with a repetition rate of 1–5 Hz, 3.8 x10^{18} W/cm^2, a_0 = 1.3 on 6mm supersonic helium gas jet with a structured gas flow with a shock front to control injection with e-beam average energy of 490 MeV, an energy spread of around 0.5%, an average integrated charge of around 30 pC, and r.m.s. divergence of 0.2 mrad.

W. Wang *et al.*, Nature **595**, 516 (2021)
See also M. Labat *et al.*, Nature Photonics 2022

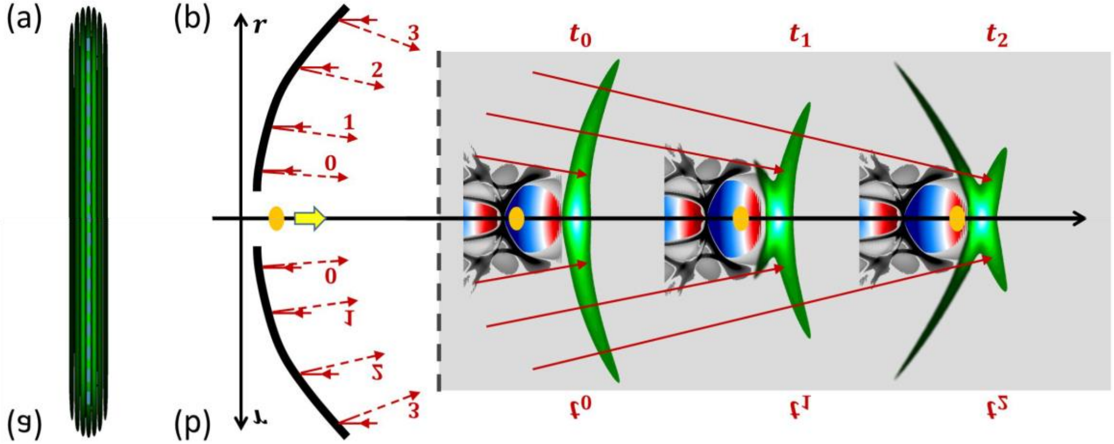
First FEL lasing from a beam driven plasma accelerator



R. Pompili *et al.*, Nature **605**, 659 (2022)

Superluminal Acceleration - Principle

- Acceleration with a diffraction-free superluminal laser beam.
- Overcoming diffraction, dephasing and depletion.



C. Caizergues *et al.*, Nature Photonics 14, 475–479 (2020)

Superluminal Acceleration - Principle

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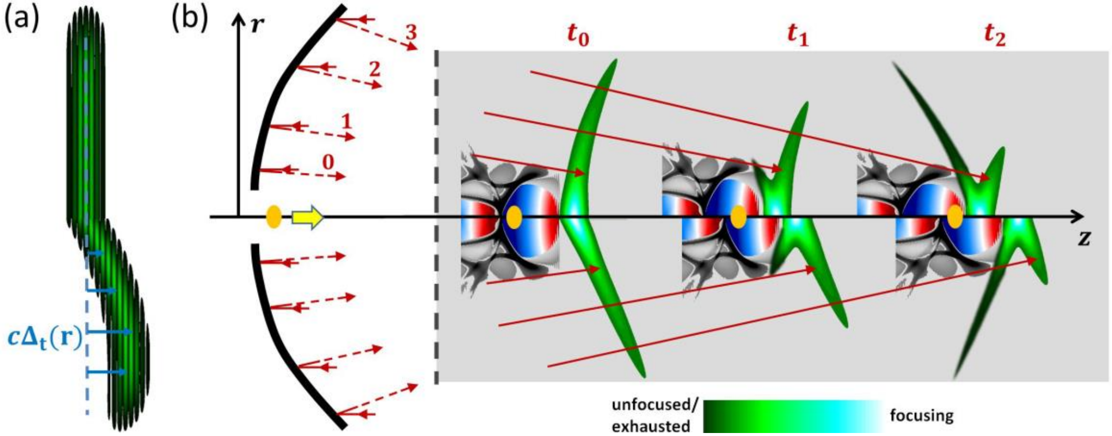


C. Caizergues *et al.*, Nature Photonics 14, 475–479 (2020)

Superluminal Acceleration - Simulations

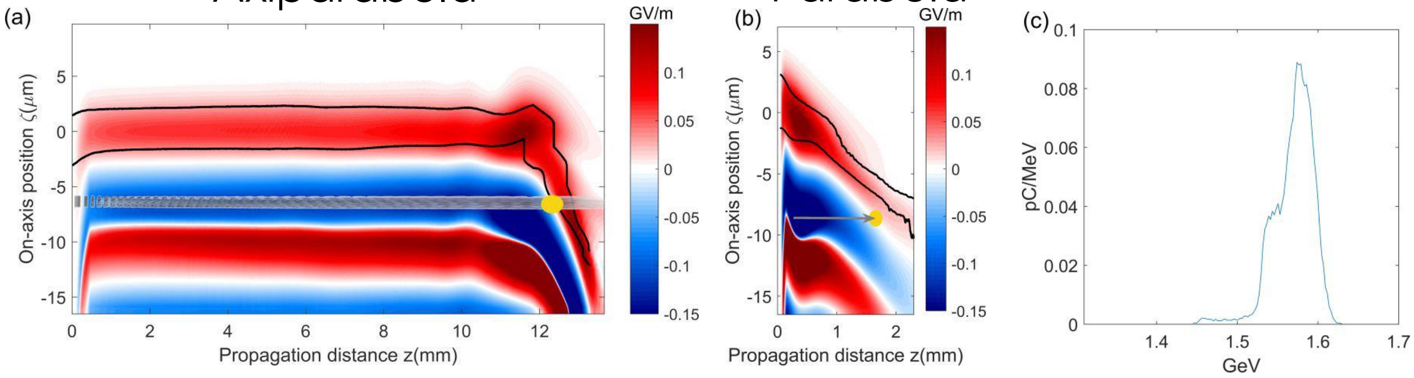
- Acceleration with a diffraction-free superluminal laser beam.
- Overcoming diffraction, dephasing and depletion.

Accelerating fields

1.6 GeV (1 J, 15 fs laser

Axiparabola

Parabola



C. Caizergues *et al.*, Nature Photonics 14, 475–479 (2020)

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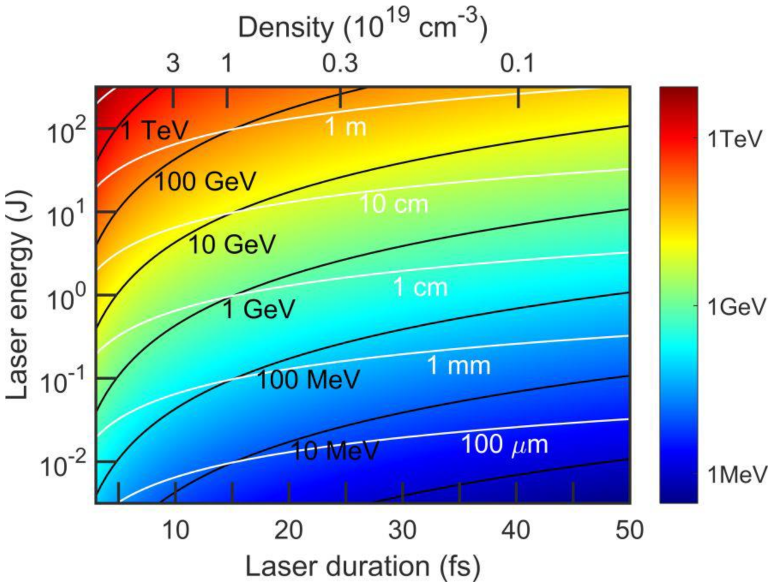
Superluminal Accel. – Scaling laws

- Acceleration with a diffraction-free superluminal laser beam.
- Overcoming diffraction, dephasing and depletion.



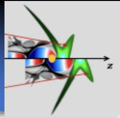
$$\gamma \propto 1/\tau^2$$

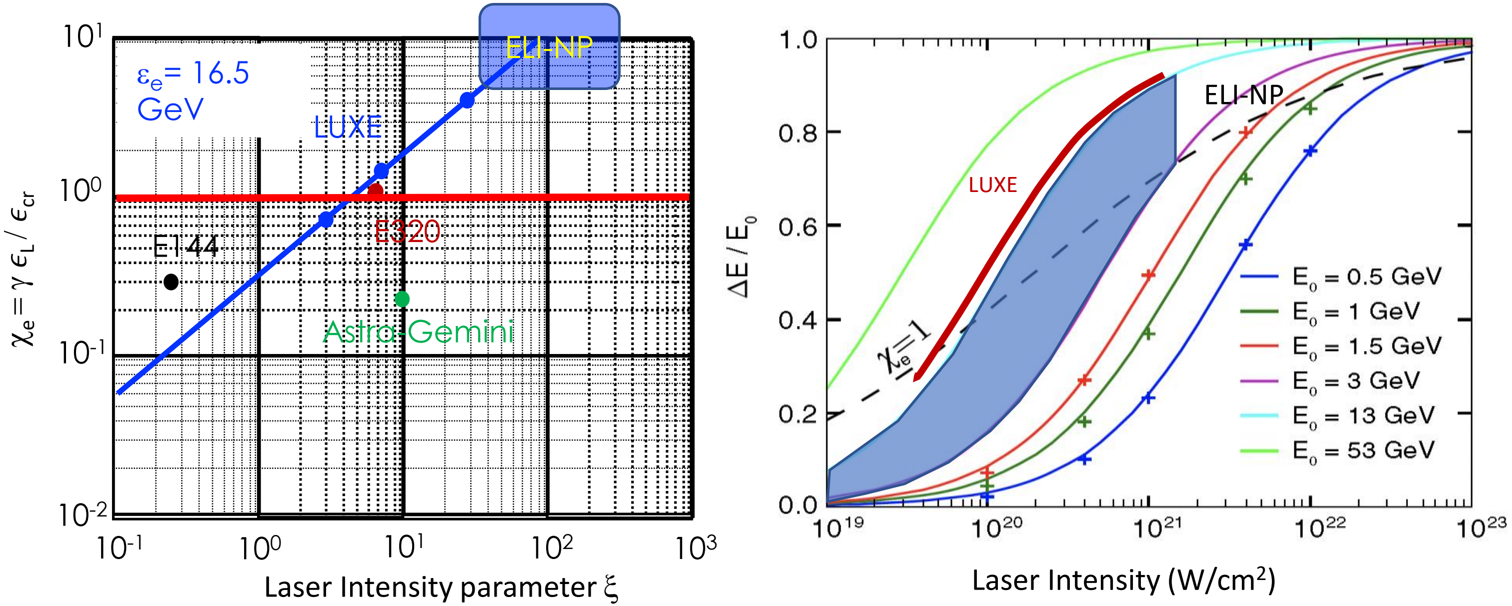
$$\gamma \propto E_L$$

Up to 50 GeV with a
1 PW, 15 fs laser

C. Caizergues *et al.*, Nature Photonics **14**, 475–479 (2020), J. Palastro *et al.*, Phys. Rev. Lett. **124**, 134802 (2020), A. Debus *et al.*, Phys. Rev. X **9**, 031044 (2019)

Strong Field QED: towards unexplored regime

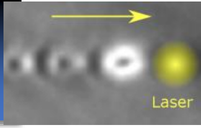




The χ_e and ξ parameter space accessible by various experiments, and on right, the relative electron energy lose $\Delta E/E_0$ as a function of the interacting intense laser. The dashed black line corresponds to the value $\chi_e = 1$, where χ_e is the ratio between the maximal laser electric field amplitude in the electron rest frame and the critical Schwinger field

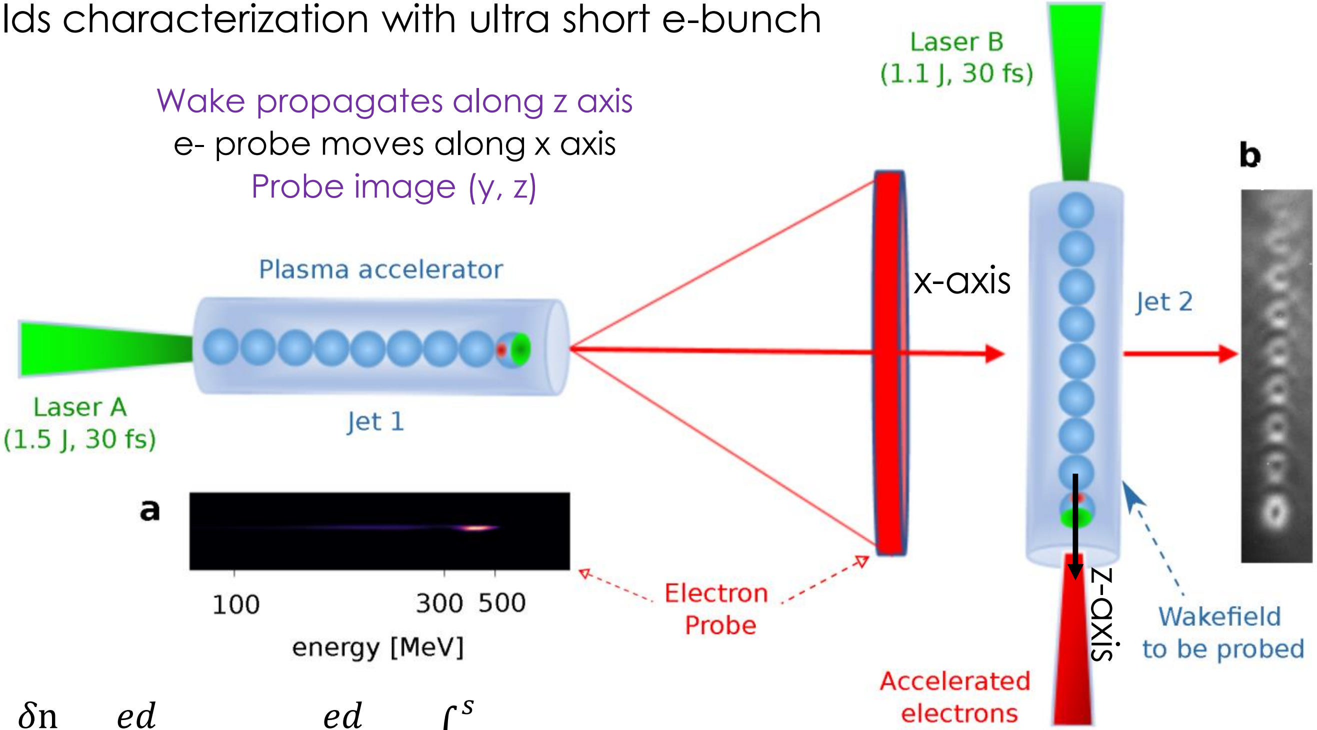
*M. Vranic *et al.*, Phys. Rev. Lett. **113**, 134801 (2014)

An insight of Non-Linear Laser Wakefield



E-fields characterization with ultra short e-bunch

Wake propagates along z axis
e- probe moves along x axis
Probe image (y, z)



$$\frac{\delta \mathrm{n}}{n} = \frac{ed}{cp_0}\nabla \cdot p_{\perp} = \frac{ed}{cp_0}\nabla \cdot \int_{-s}^{s}(E + v \times B)dx$$

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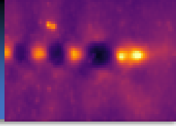
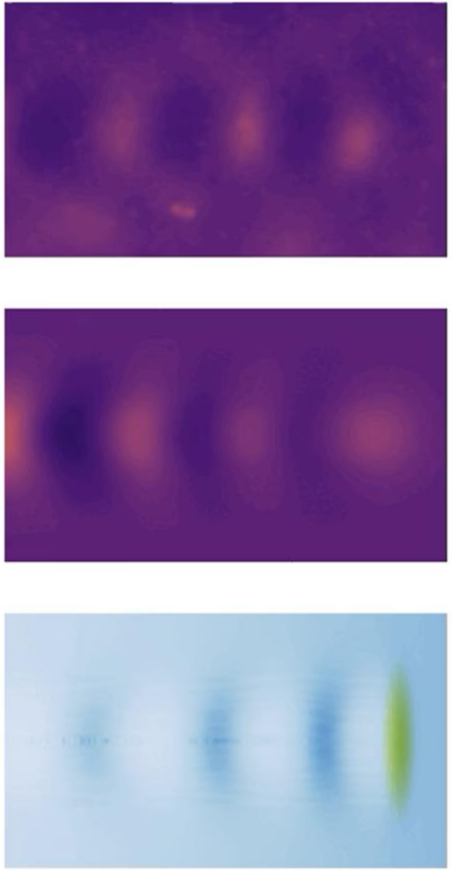
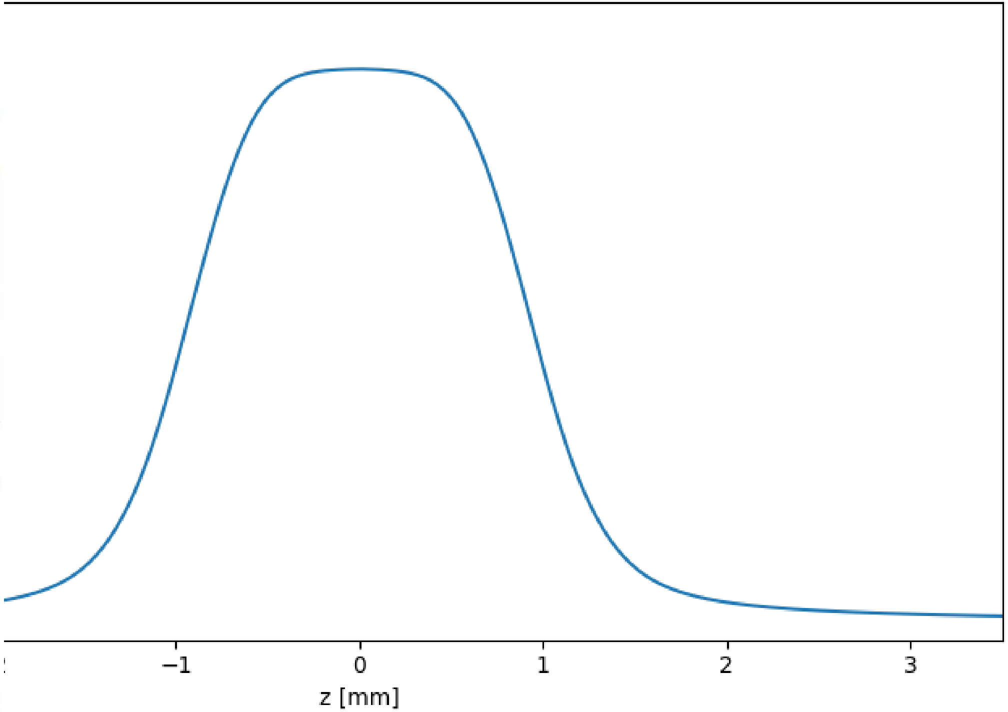
Transition from the laser to the plasma wakefield







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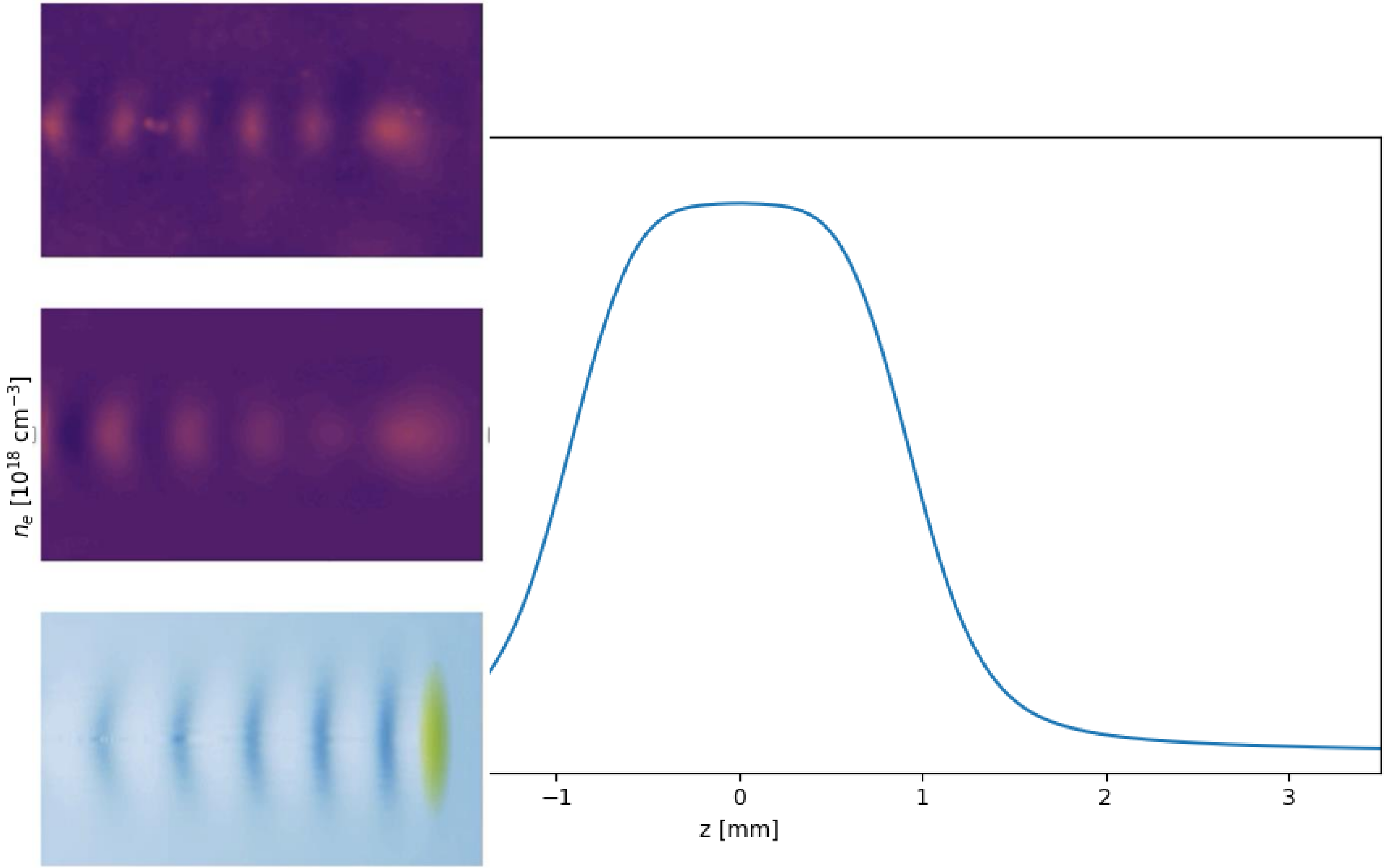

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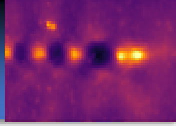
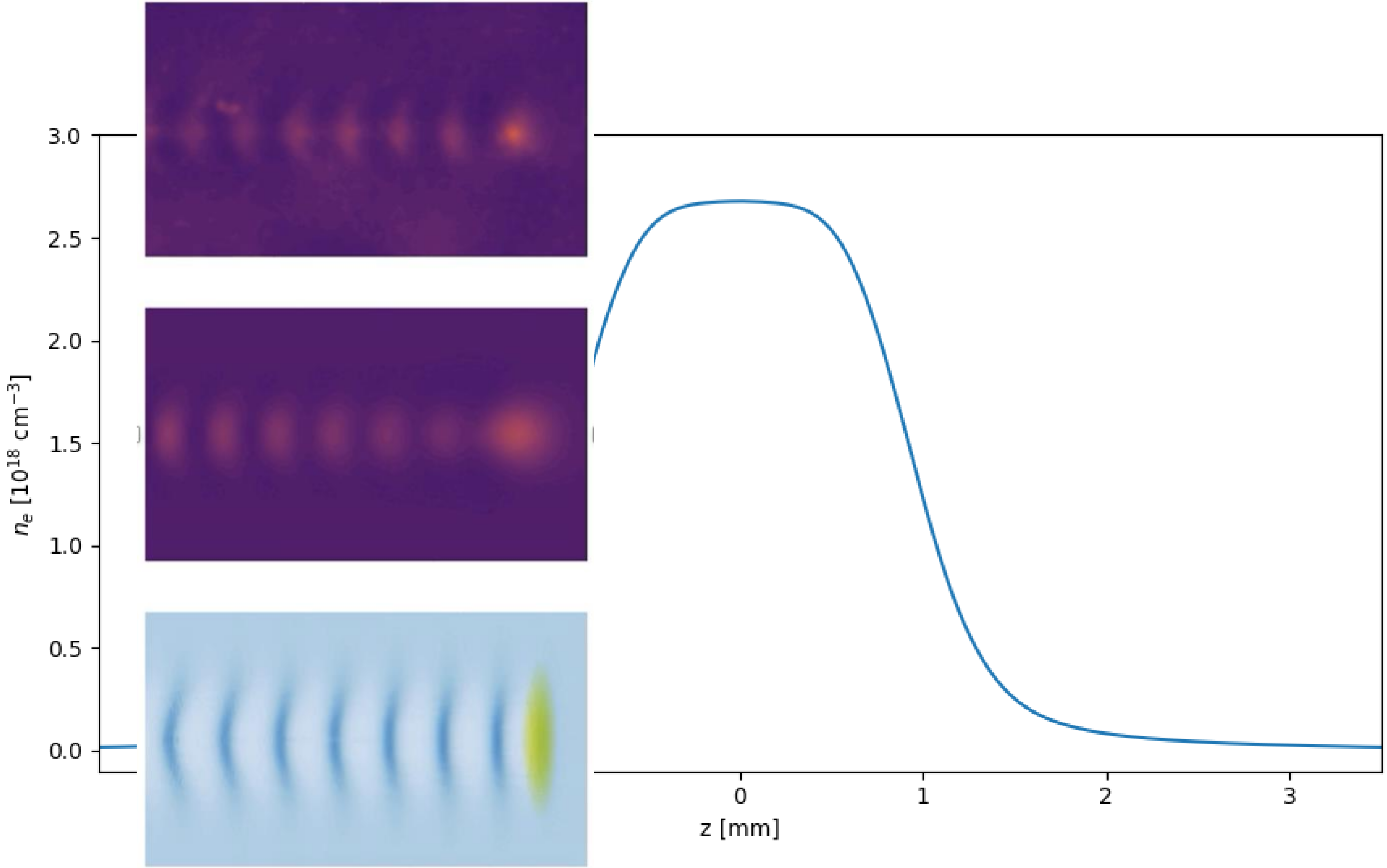
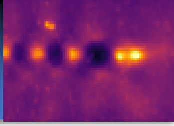
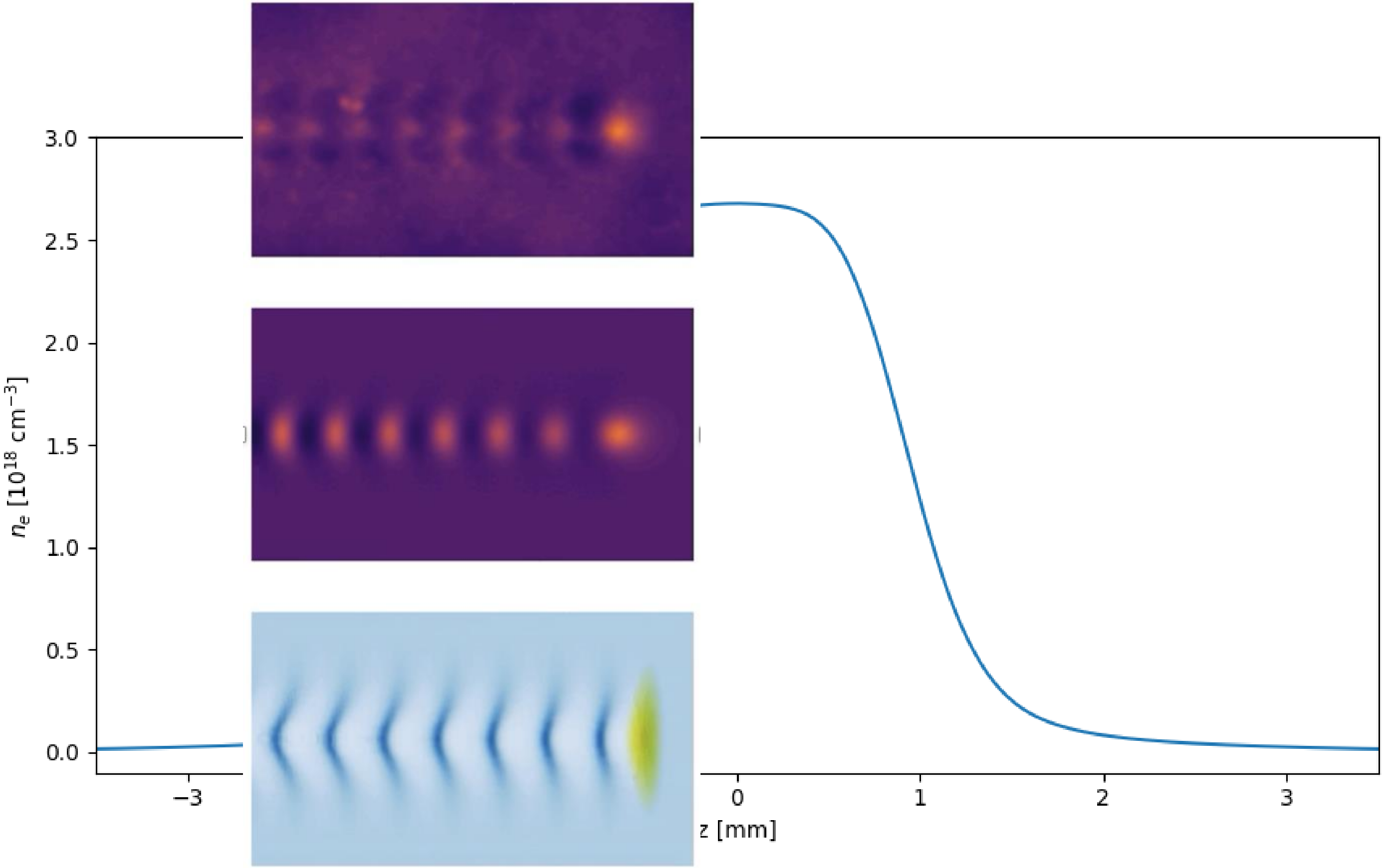




Transition from the laser to the plasma wakefield





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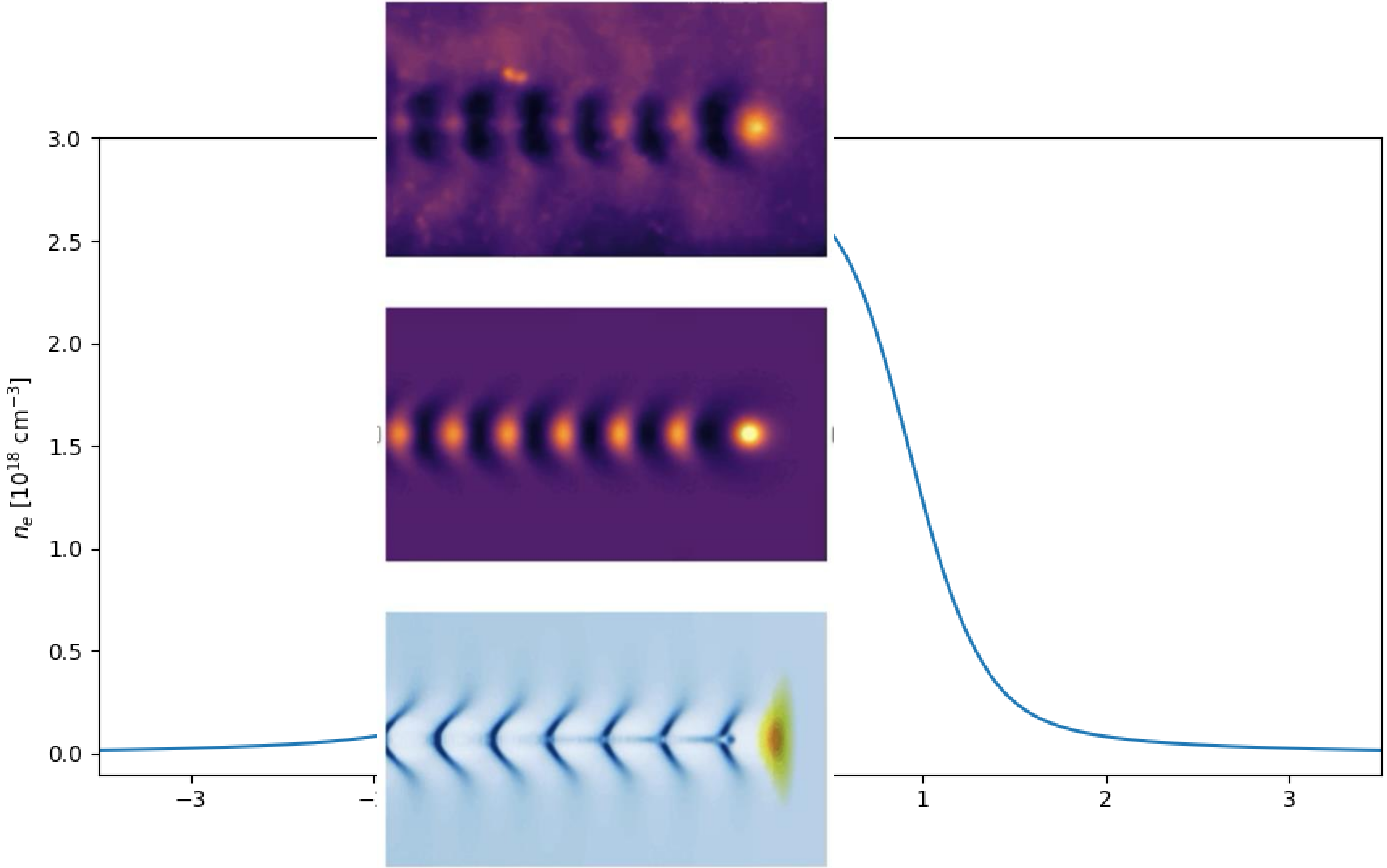
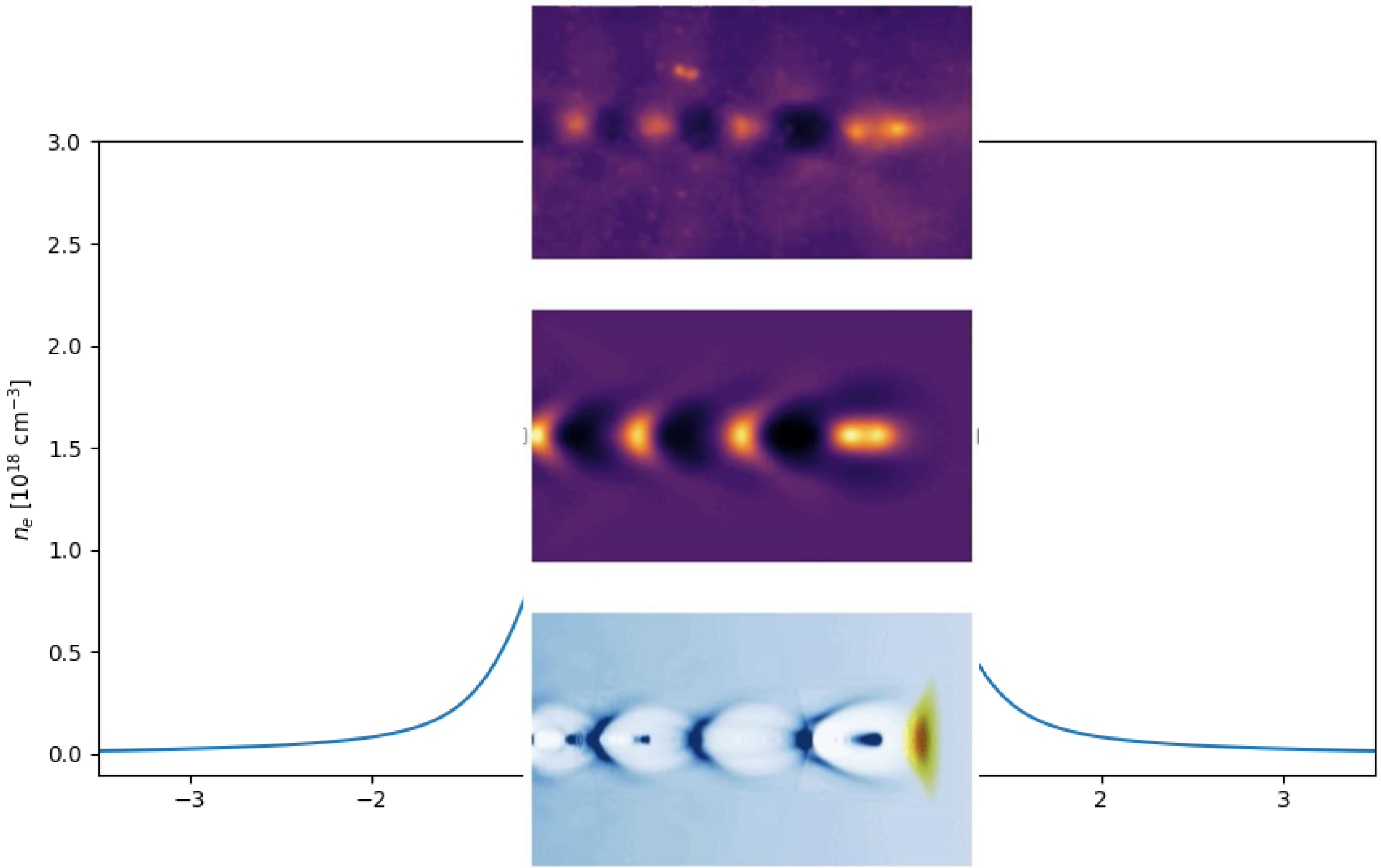


Transition from the laser to the plasma wakefield



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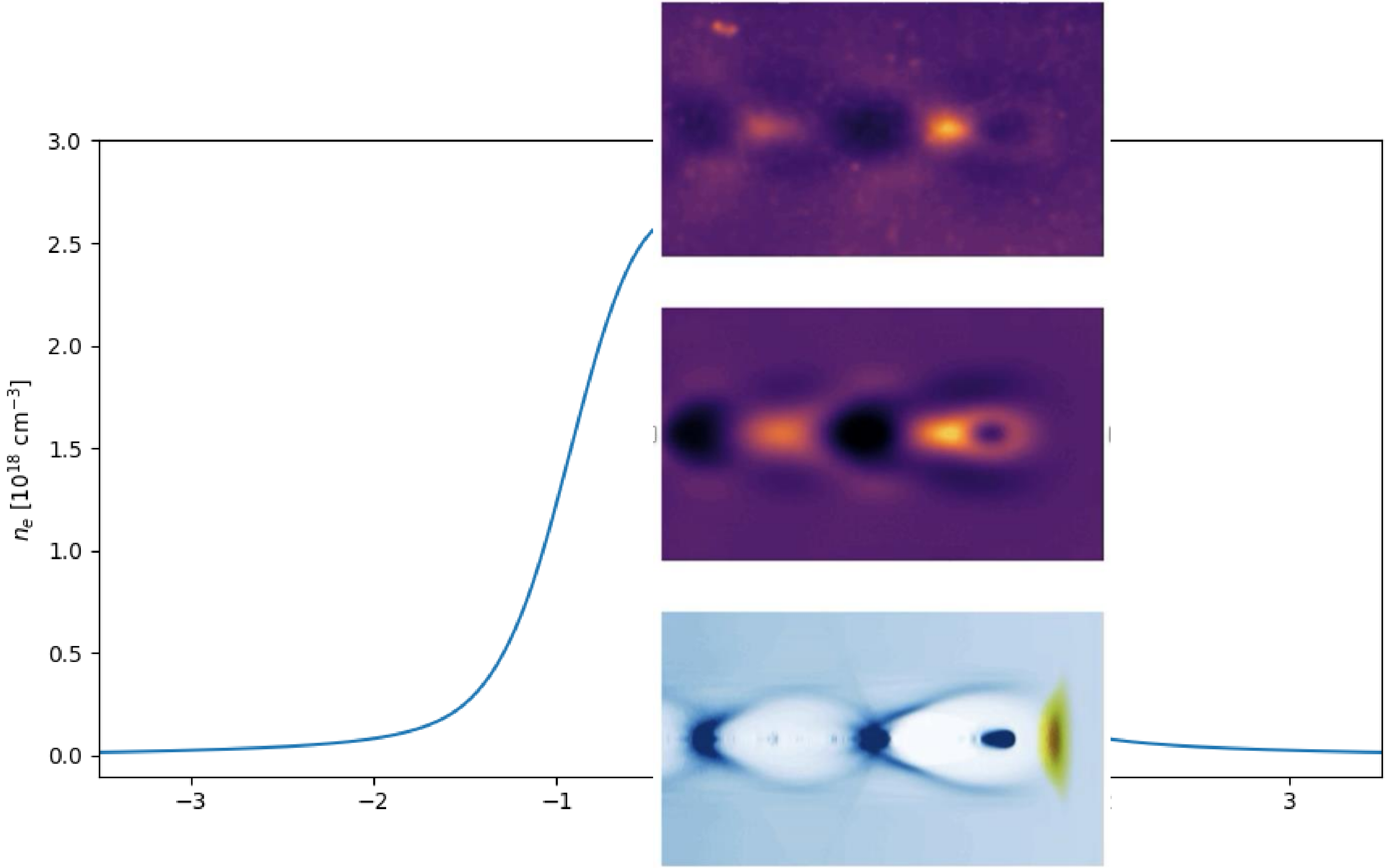
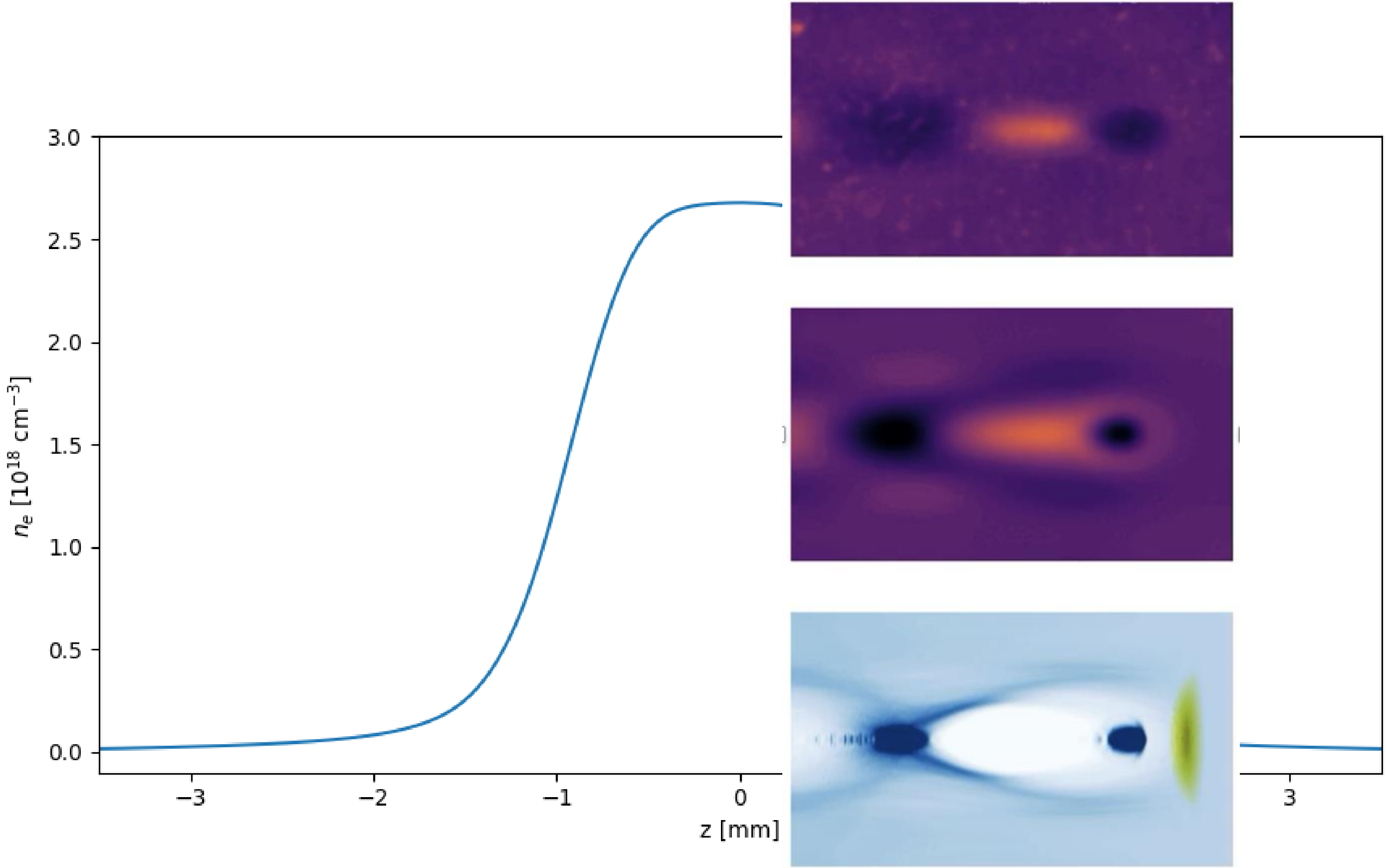
Transition from the laser to the plasma wakefield



Transition from the laser to the plasma wakefield



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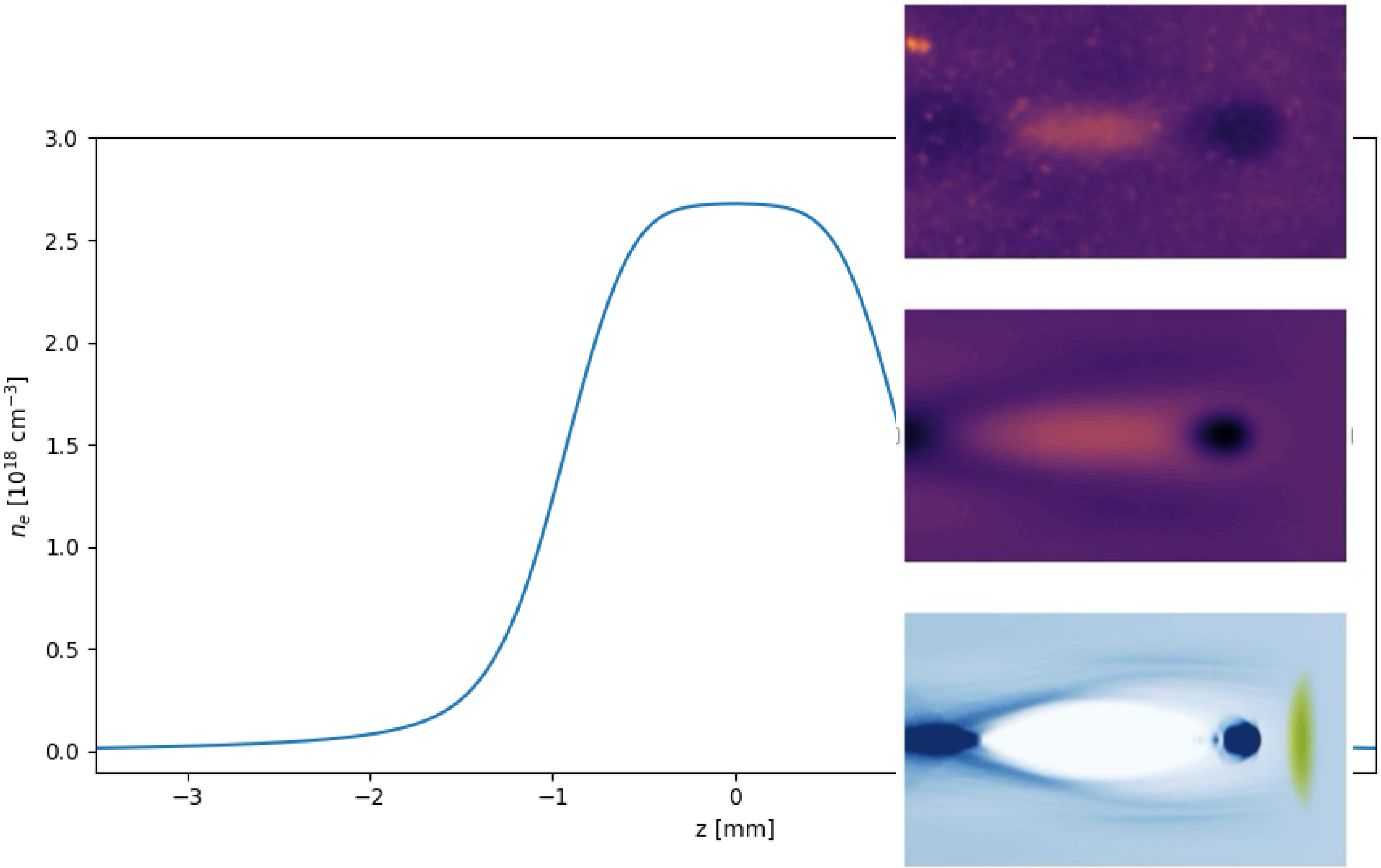
Transition from the laser to the plasma wakefield



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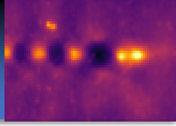
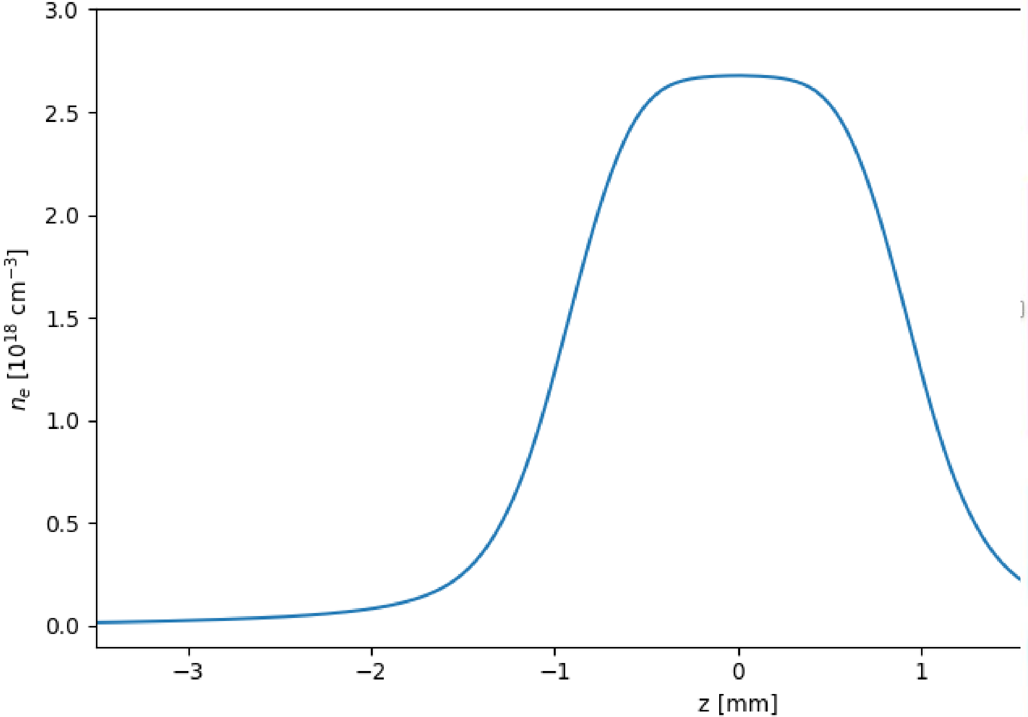
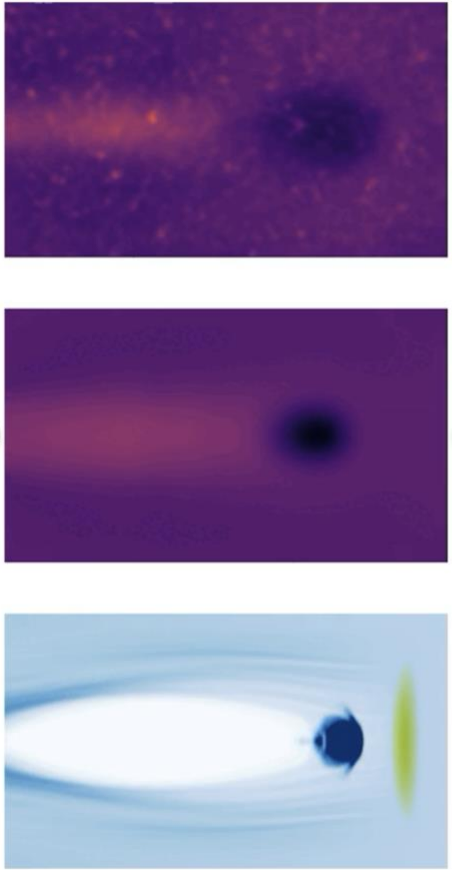
Transition from the laser to the plasma wakefield







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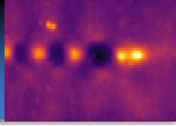
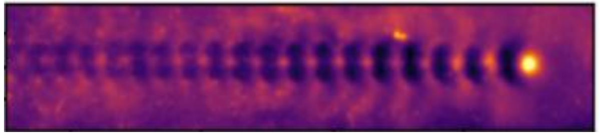
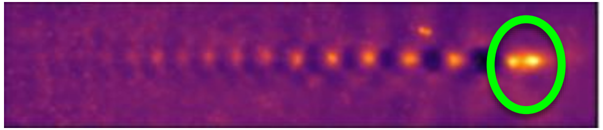
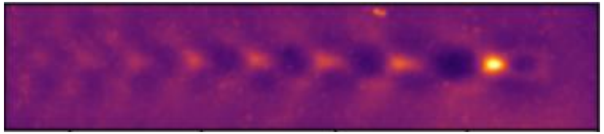




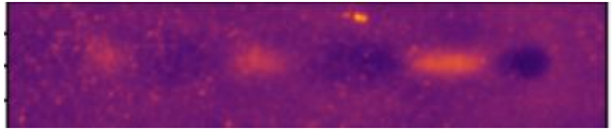
Pure LWF



Electron injection in LWF



Mixed PWF and LWF



Pure PWF

Y. Wan *et al.*, Science Advanced eadj3595 (2024), Light: Science & Applications **12** (1), 116 (2023), Nature Physics (2022),

Conclusion & perspectives

- ✓ LPAs are delivering stable and high-quality electron beams
- ✓ Few J/ 30fs / 10 Hz lasers deliver in routine high-quality e-beam at 100s MeV
- ✓ Few mJ/ few fs/ kHz lasers deliver in routine high-quality e-beam in 10s MeV
- ✓ Few 10s of J/ 30fs/ 1 Hz lasers deliver GeV-10 GeV e beam
- ✓ Impressive progresses have been done in guiding intense laser pulse, but high-quality beams are not yet there
- ✓ LPAs are mature for delivering compact X ray sources such as Thomson, Compton, Betatron, and now FEL
- ✓ LPAs are mature to challenge applications in security, radiotherapy, ultrafast phenomena studies, etc…
- ✓ LPAs are pertinent for High Fields Sciences

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Conclusion & perspectives

- ✓ New diagnostics are helping in getting better temporal and spatial resolutions
- ✓ New numerical schemes, genetic algorithms and artificial intelligent also appeared these 10 years
- ✓ Laser technology is proposing more products opening also new direction of research
- ✓ More than one 100 University labs,
- ✓ Crucial in the major projects such as ELIs, LBNL, APOLLON, SIOM, CORELS, KIST, etc…
- ✓ All together this indicates a vivant area of research with a bright and exciting future.

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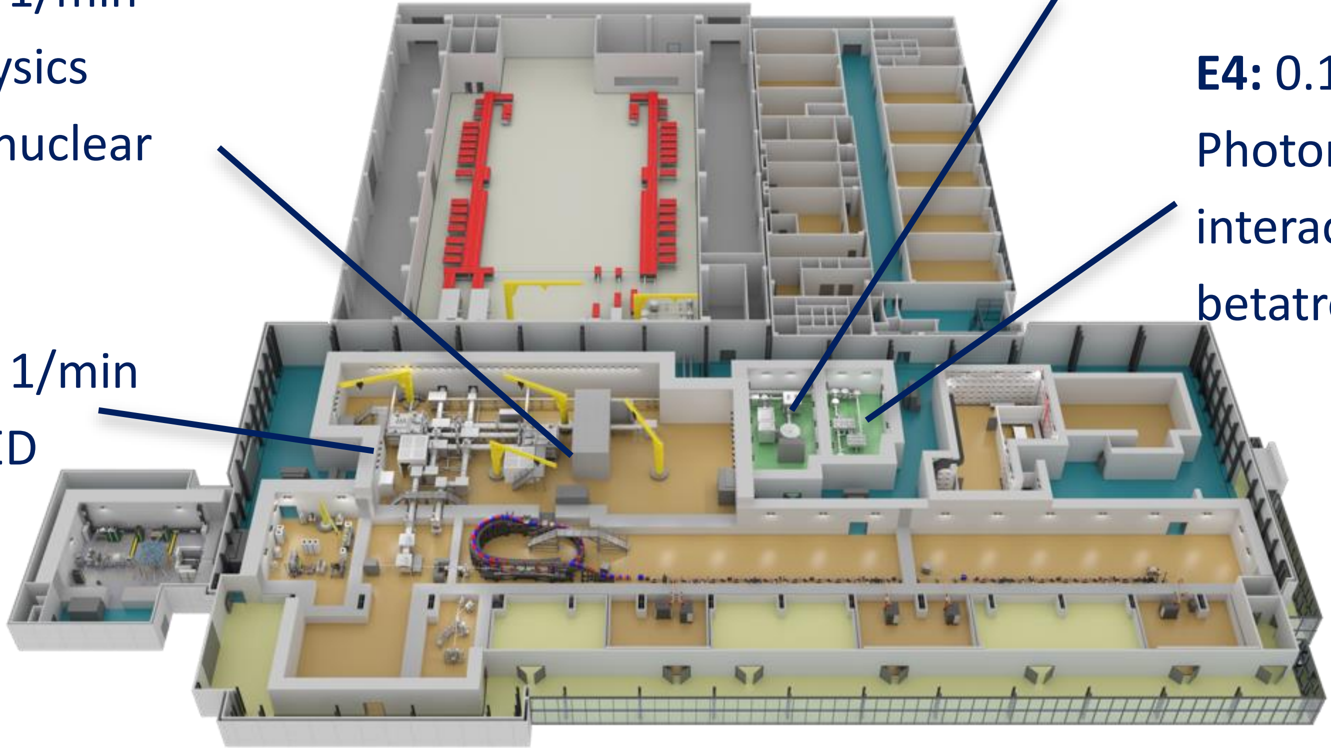

E1: 10 PW @ 1/min

High field physics

Laser driven nuclear physics

E6: 10 PW @ 1/min

High Field QED

E5: 1 PW @ 1 Hz

E4: 0.1PW@10 Hz

Photon-photon interaction,LWFA, betatron

or at WIS