SIMULATIONS OF A WAKEFIELD DISSIPATION IN A RADIALLY BOUNDED PLASMA

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Essence in brief

We study long-term evolution of the plasma wakefield after passage of a dense electron bunch (in the blowout regime).

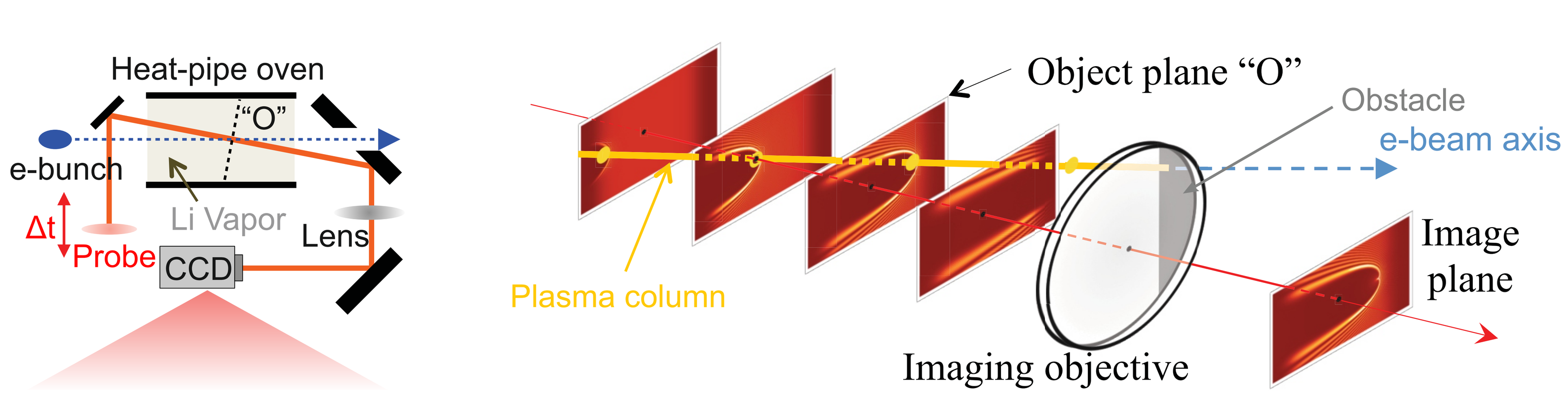
Experiments at FACET (optical shadowgraphic measurements) show rapid plasma expansion at a nearly constant speed.

Simulations quantitatively agree with measurements and uncover mechanisms of wakefield energy conversions and plasma expansion:

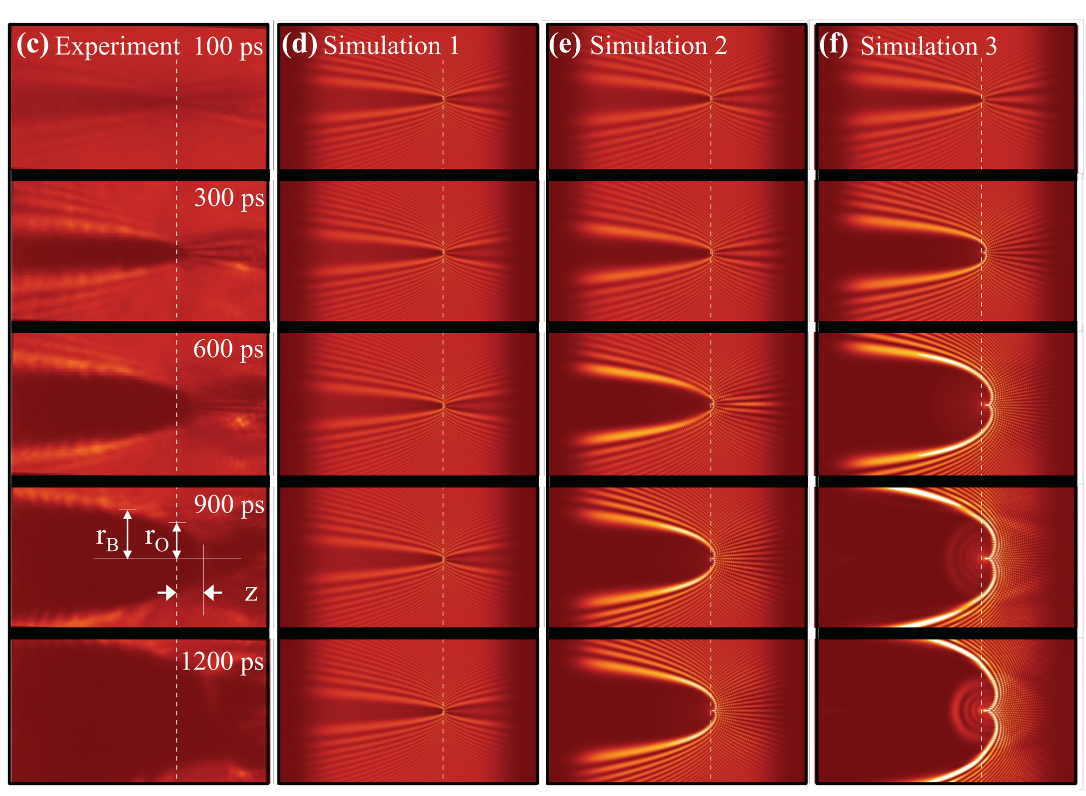
- first, the wave breaks, and its energy goes mostly to fast (tens of keV) electrons, which tries to escape from the plasma;
- fast electrons create charge separation electric field, which holds most electrons near the plasma and halves their total energy
- electric field accelerates ions radially, and eventually ions acquire most of the plasma energy
- radially moving fast ions ionize the surrounding neutral gas (impact ionization), create low-density plasma there and make these regions accessible to warm plasma electrons
- growth of electron population triggers near-exponential plasma density growth through electron impact ionization (mainly two-step process through excited states).

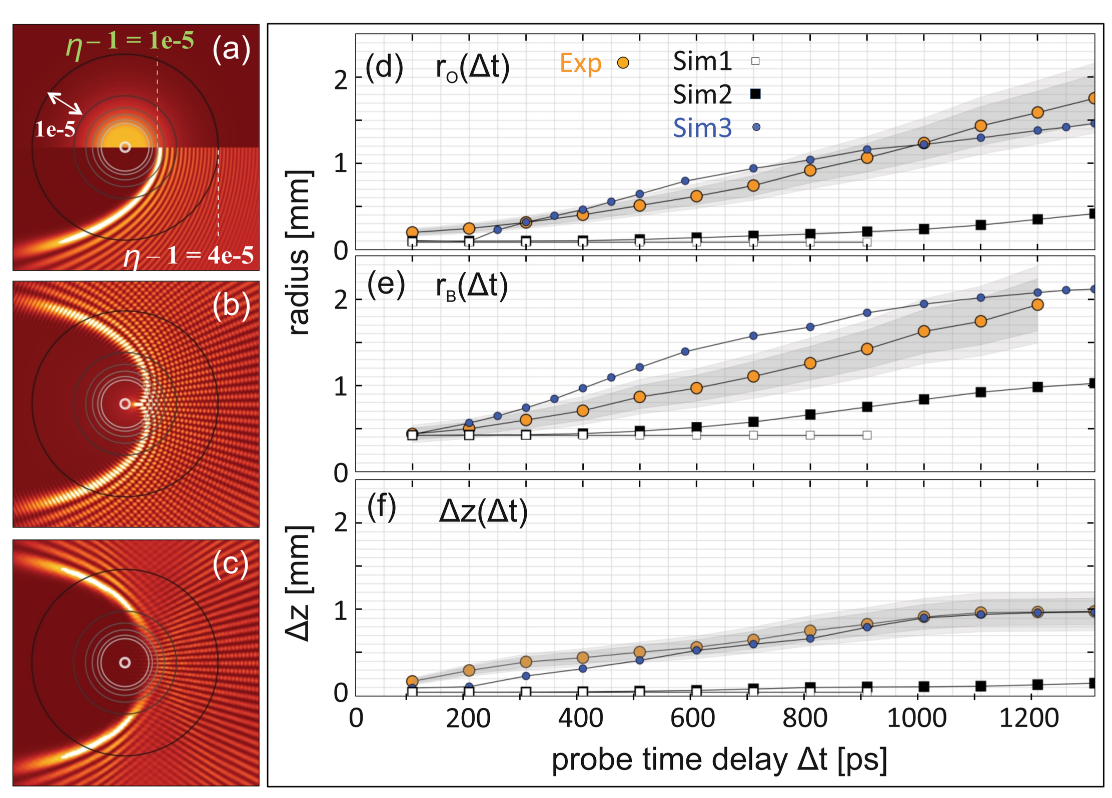
90% of the wake's initially deposited energy remains within the plasma column for over a nanosecond, and major part of this energy is kinetic energy of radially moving ions.

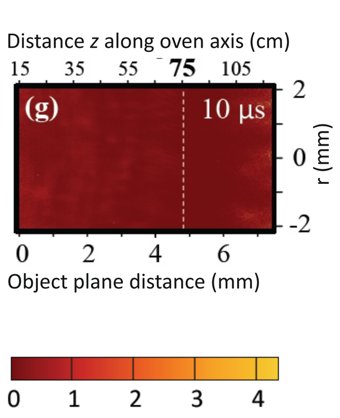
Experiments at FACET



e-bunch energy	20 GeV
e-bunch charge	2.4 nC
transverse rms e-bunch size	30 μm
longitudinal rms e-bunch size	55 μm
laser wavelength	0.8 μm
laser energy	1 mJ
laser duration	0.1 ps
laser FWHM at focus	0.5 cm
plasma density	8 10^{16} cm^{-3}
plasma length	1.5 m
angle	0.008 rad



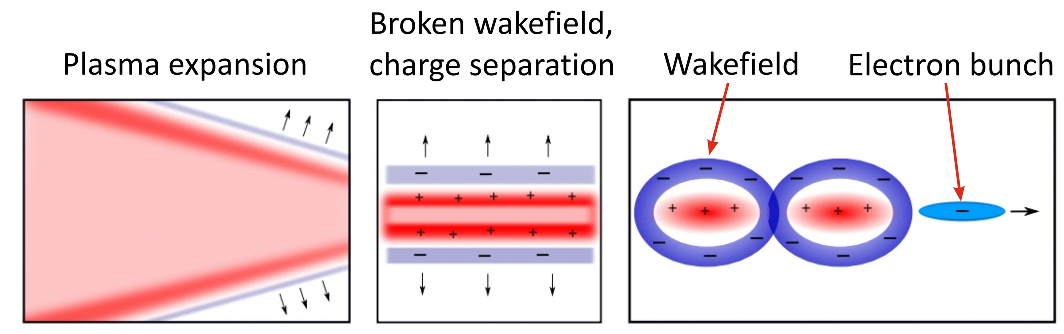




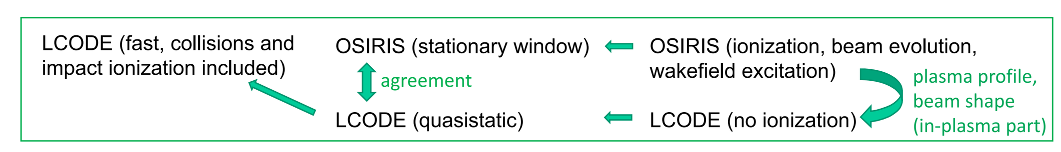
Imaging of expanding Li⁺ ion column following electron wake excitation. (c) Experimental probe images, normalized to unperturbed probe intensity I_0, averaged over 30 shots. Dashed vertical white lines: intersection of "O" with plasma column. Each probe image is 4mm high × 7.5mm wide; horizontal dimension corresponds to projected distance 1.0 m along plasma column axis.
(d)-(f) Simulated probe images for three plasma expansion models:
(d) including dynamics of ions within initial plasma column only;
(e) including impact ionization of ground state neutral lithium surrounding initial plasma column;
(f) including impact excitation of neutral lithium to 2P, 3S, and 3P states and impact ionization.
(g) Experimental probe image at Δt = 10 μs, for which plasma column expanded well beyond field of view.

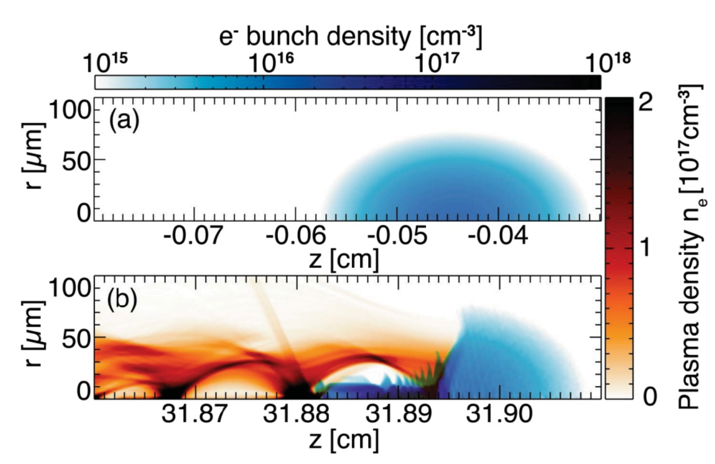
Comparison of probe image features with simulation results. (a)-(c) Electromagnetic simulations showing how probe intensity profile evolves thru plasma column to detector: **(a) Top half:** typical refractive index cross-section η(r) of plasma column at object plane "O", with column axis tilted at 8 mrad to page normal from left (back) to right (front); circles: black index contours in $\Delta\eta = 10^{-5}$ increments; **bottom half:** radial intensity profile of probe, propagating normally out of page, at "O", showing light penetration to $\eta - 1 = 10^{-5}$ contour, parabolic shadow and surrounding interference fringes; **(b)** corresponding probe profile after ideal imaging to detector, showing axial caustic and orthogonal interference fringes acquired in passing through remainder of plasma column;
(c) corresponding probe profile after non-ideal imaging to detector, showing re-shaping of vertex region due to partial blockage of imaging lens. **(d)-(f)** Plots of (d) $r_O(\Delta t)$, (e) $r_B(\Delta t)$ and (f) $\Delta z(\Delta t)$ from measured probe images (orange-filled circle data points), showing 1σ (dark grey) and 2σ (light gray band) variations over 30 shots, and from the three theoretical models: no impact ionization (open grey squares), ground state impact ionization (filled black squares), impact excitation + impact ionization (filled blue circles).

Stages of wake evolution



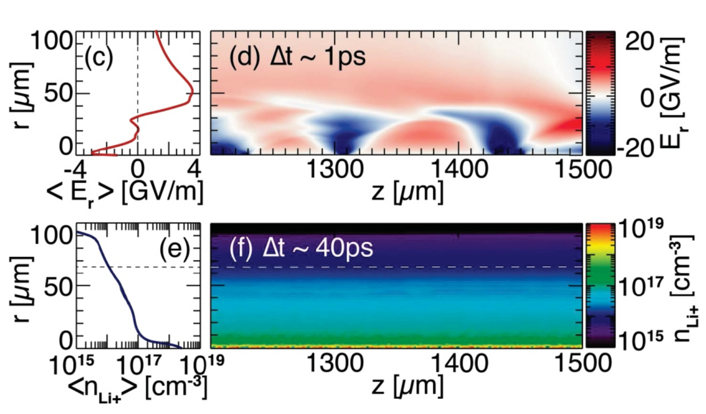
$t \le 1.5$ ns, $v \sim 10^6$ m/s	$t < 40$ ps	$t \sim 1$ ps
The plasma (dark region on the image) expands radially	The wave breaks after few periods, creating high-energy electrons (up to 100s keV) and charge separation fields to keep plasma quasi-neutrality	The electron bunch ionizes the lithium, creates a plasma cylinder (radius ~ 40 μm), and drives the strong wakefield in it (nearly full blowout)





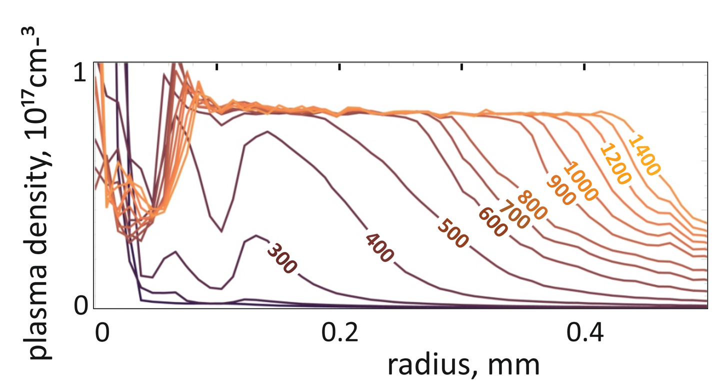
Stage 1:

OSIRIS simulation results. Drive bunch profile at (a) z < 0 (blue), before entering Li vapor at z = 0, and at (b) z ~ 32 cm, after entering the Li density plateau, focusing, and creating trailing beam-ionized plasma and electron wake (orange).



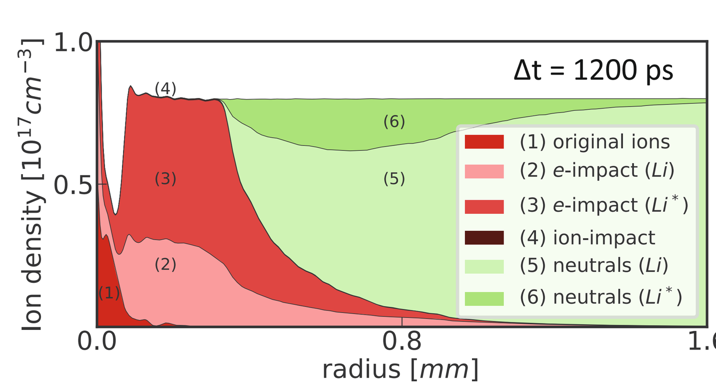
Stage 2:

(c) Longitudinally-averaged and (d) full radial electric field Er(r, z) profiles at t ~ 1 ps after the driver passes.
(e) Longitudinally-averaged and (f) full ion density at t ~ 40 ps after driver passage. Dashed line indicates the maximum r ≈ 65 μm to which drive bunch directly ionized Li.



Stage 3:

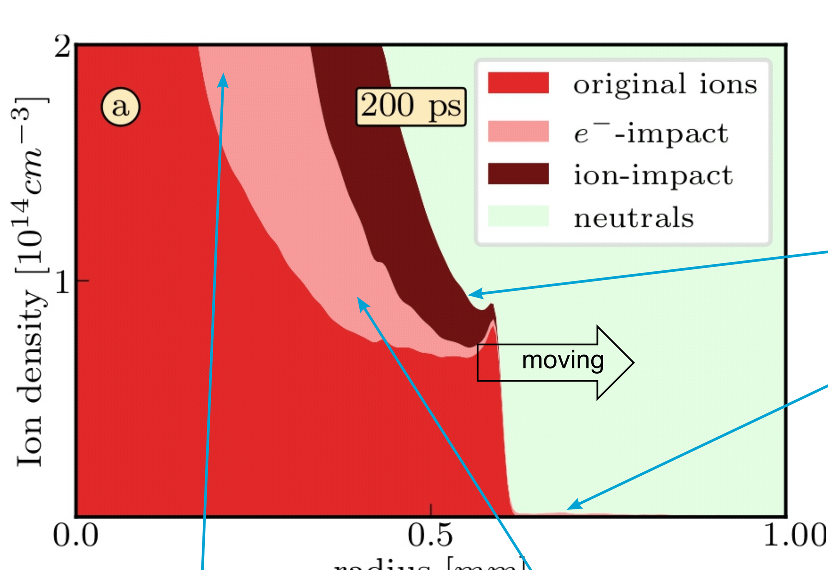
LCODE simulations of evolving plasma density. Labels on individual curves denote time in ps.



Origin of new ions:

Relative contributions of original ions (region 1) and of electron-impact-ionized ground-state (2) and excited (3) neutrals, while the barely visible region 4 indicates ion-impact-ionized Li atoms.

Initial ionization

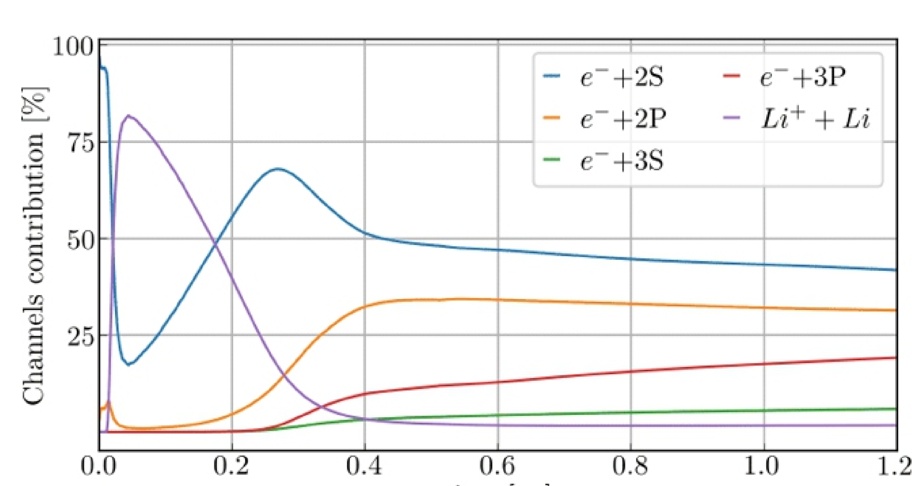


2. Original ions are accelerated to multi-keV energies and efficiently ionize neutrals (many new ions per original ion). A moving front of fast ions creates more ions than it has.

1. High-energy electrons, which enter the surrounding gas first, ionize inefficiently, as their density is low and ionization cross-section is small because of a high energy.

4. Growth of electron population triggers near-exponential plasma density growth.

3. Once ions appear at a given location, more electrons come, including lower-energy plasma electrons with large impact-ionization cross sections, and speed-up ionization.

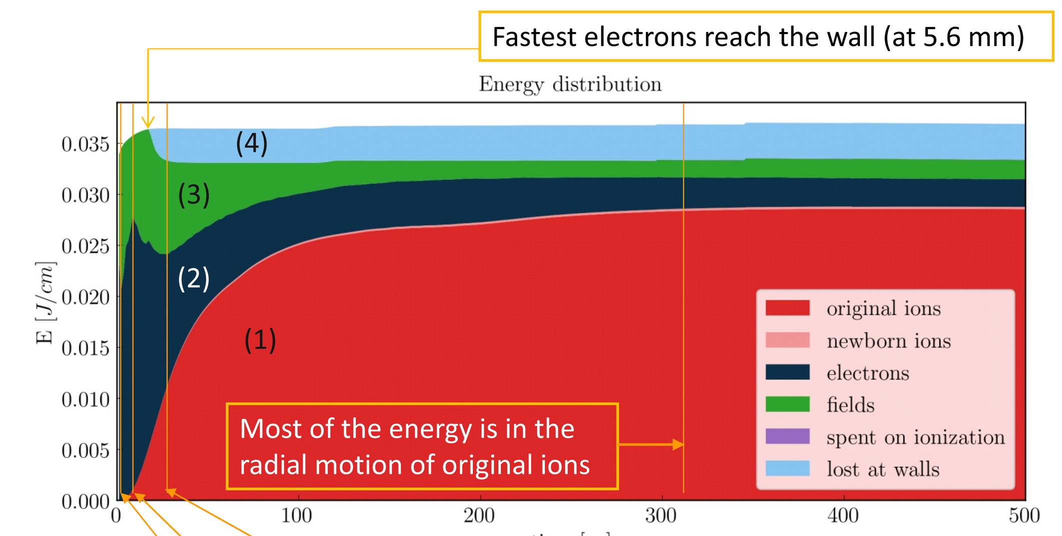


Relative contributions of different ionization channels. Dominates:

t < 20 ps:	electron impact (before ions gain energy)
20 ps < t < 200 ps:	ion impact
200 ps < t < 500 ps:	single-step electron impact
t > 500 ps:	two-step electron impact

Energy budget

Fastest electrons reach the wall (at 5.6 mm)



Most of the energy is in the radial motion of original ions

Charge-separation field comes to equilibrium with electron distribution (energies equal), ions accelerated

The wave breaks, most of the energy is in hot electrons

Initial wakefield energy is in fields and in electron motion

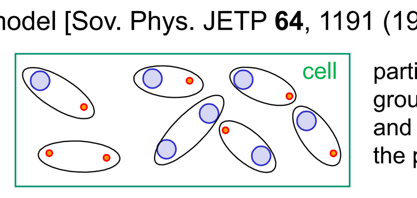
Hot electrons carry ~ 10% of the energy deposited in the original wake to the walls in the first ~ 20 ps (region 4). The expanding plasma column retains the rest without noticeable attenuation throughout the remainder of the simulated period. Radially propagating electrons (2) and fields (3) carry most of the latter energy initially (20 ≤ Δt ≤ 40 ps), but transfer ~ 85% of it to radial ion motion (1) within 300 ps.

Technical details

Fields and motion of charged particles: main effect that wakefield codes simulate, well benchmarked

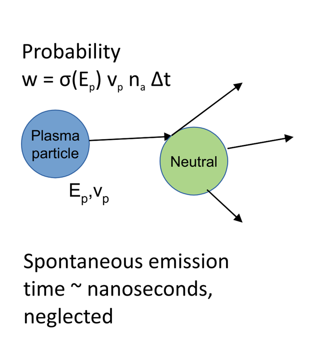
Ionization by the driver: Ammosov-Delone-Krainov (ADK) model [Sov. Phys. JETP **64**, 1191 (1986)].

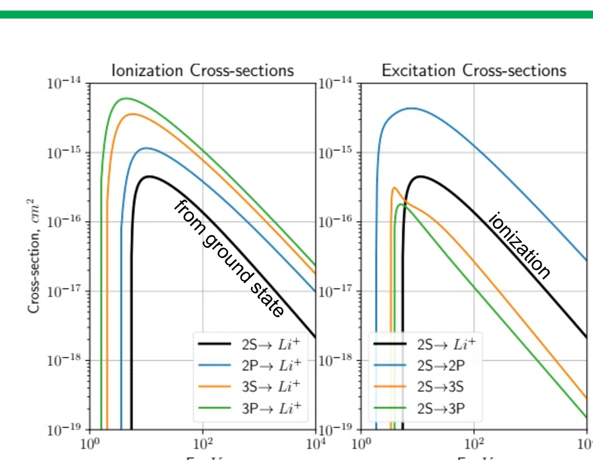
Coulomb collisions: Takizuka-Abe model
[J. Comp. Phys. **25**, 205 (1977)]
modified to include relativistic particles
[F. Perez, et al., Phys. Plasmas **19**, 083104 (2012)].



particles in a cell grouped in pairs and scatter on the partners

Impact ionization and excitation by plasma particles: cross-sections from IAEA Aladdin database for electron impact and from theoretical model [I. D. Kaganovich, et al., New J. Phys. **8**, 278 (2006)] for ion impact.





More info: arXiv: