Nonlocal collisionless phenomena in Plasmas
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A. Dunaevsky

Measurements in expanding plasma

Acknowledgement to Dr. Y. Raitses and Prof. N.J. Fisch

Dept. of Astrophysical Sciences
Princeton University, Princeton, NJ 08543

Diagnostics in expanding plasmas

Measurements in expanding plasmas are usually directed on gathering information about the plasma source, which is not accessible for diagnostics: short time small scale plasmas.

Scope of interests: plasma density and EEDF (or T_e) in the source

Typical examples: laser plasmas, pulsed breakdown

Diagnostic toolbox:

- probes – electron and ion density;
- Faraday cups – electron and ion fluxes;
- emissive probe – potential profile;
- energy analyzers – ion energy spectrum;
- LIF – ion velocities (energies)

Theory of the plasma expansion is required to play back the scenario!

Kinetics of expanding plasma

Kinetics of collisionless plasma expansion is described by Vlasov equation for electrons, together with Poisson equation.

Approximations:

- Quasineutrality
- Isothermal expansion of plasma from semi-infinite source
- Boltzmann distribution for electrons

This problem has well-known self-similar solution

☐ A.V. Gurevich, L.V. Pariiskaya, and L.P. Pitaevsky, *Sov Phys. JEPT* **22**, 449 (1966)

Self-similar solution depends on $x/c_s t$ and applicable only at distances >> λ_{D0}

Solutions for adiabatic expansion

Isothermal solution describes plasma expansion from source with infinite mass and energy and inapplicable for short discharges with limited energy and plasma volume.

Recently, 1D self-similar problem for adiabatic expansion has been solved analytically:

- A.V. Baitin, K.M. Kuzanyan, *J. Plasma Physics* **59**, 83 (1998)
- D.S. Dorozhkina, and V.E. Semenov, *Phys. Rev. Lett.* **81**, 2691 (1998)
- V. S. Kovalev, V. Yu. Bychenkov, and V. T. Tichonchuk, *Sov. Phys. JETP* **95**, 226 (2002)

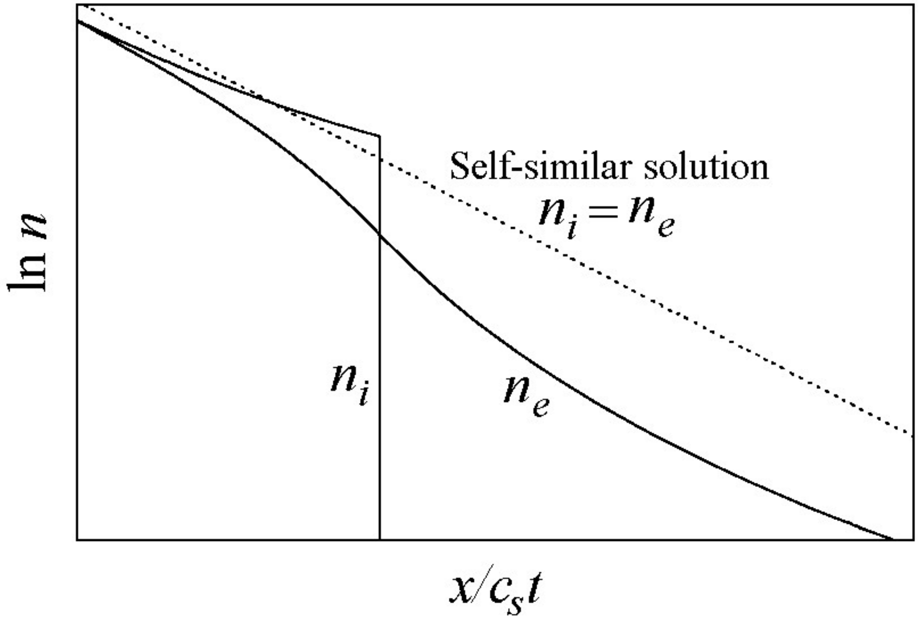
If evolution of density profile *n(x,t)* in the plasma bulk is known, information about initial plasma parameters n_0 and λ_{D0} in the source can be deduced from the self-similar solution. In 1D approximation at $T_e >> T_i$

$$n(x,t) \approx \frac{n_0}{\sqrt{1+\Omega^2 t^2}} \exp\left(-\frac{U^2}{2c_s^2}\right); \quad \Omega^2 \sim 2\frac{c_s^2}{\lambda_{D0}^2}; \quad U(x,t) = \frac{\Omega x}{\sqrt{1+\Omega^2 t^2}}$$

Applicability of the self-similar solution

Self-similar solution does not resolve the non-neutral region at the front of expanding plasma.

After the front, however, both solutions are close. Experiments on the triple plasma device also showed the similarity of the bulk plasma expansion to the self-similar solution.



❑ C. Chan, N. Hershkowitz, A. Frreira, T. Intrator, B. Nelson, and K. Lonngren, *Phys. Fluids* **27**, 266 (1984)

❑ P. Mora, *Phys. Rev. Lett.* **90**, 185002 (2003)

Thus, self-similar solution is applicable for density profiles of the bulk plasma => Initial plasma parameters may be deduced from the ion density profiles.

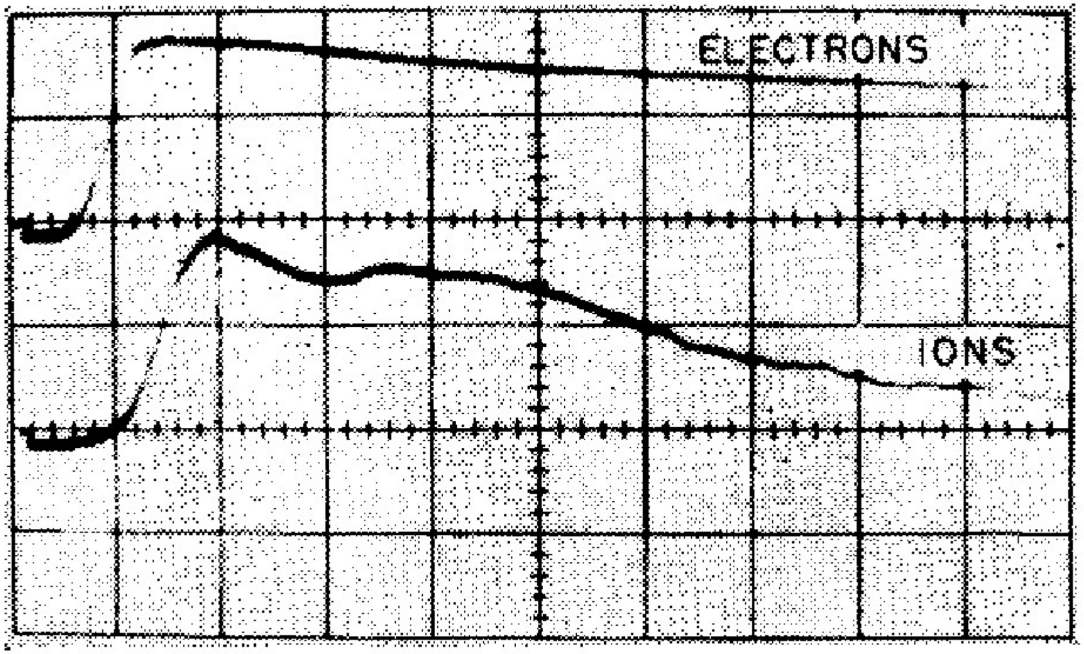
Electron density profiles differs substantially from the self-similar solution and forms an “electron advance”

Density profiles

Electron advance was observed experimentally more than 40 years ago in the pulsed discharge on SiC surface

Measurements were taken by Langmuir probes

For high voltage pulsed discharges, electromagnetic noise is a considerable problem.

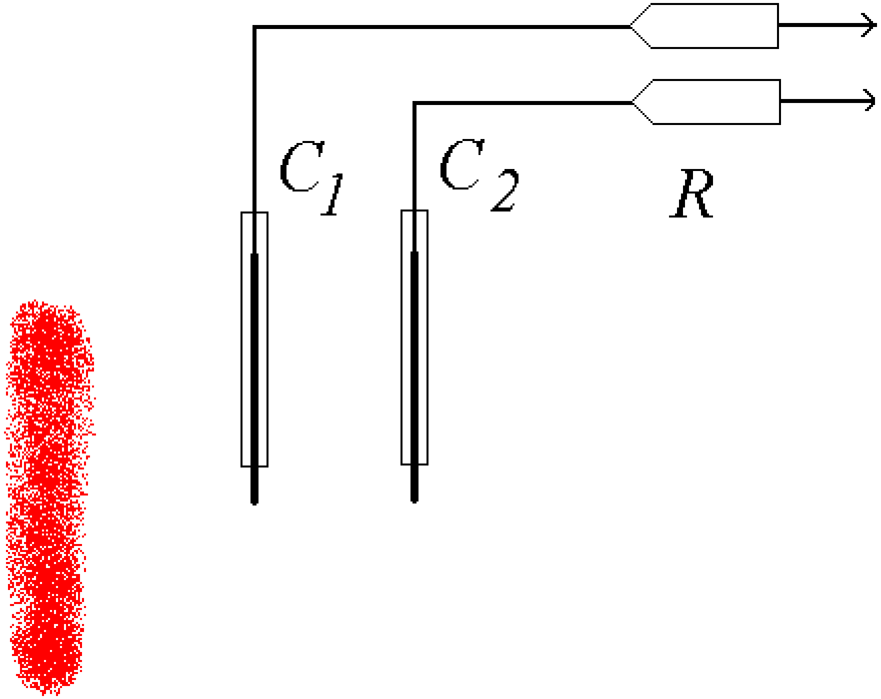


❑ H.W. Hendel and T.T. Reboul, *Phys. Fluids* **5**, 360 (1962)

Floating probes in expanding plasma

In noisy environment, electron advance at the front of expanding plasma can be useful.

Self capacitance of a floating probe can be charged by the advance electrons. If the probe resistance *R* is much higher than the sheath resistance, the discharge of the probe capacitance will occur mostly due to ion current to the probe.



Assumptions

- Distance to the probes $l >> \lambda_D$
- Time scale of plasma formation is much less than the expansion time scale: $\tau_p << t$
- Initial electron distribution is close to Boltzmann: $\nu_{ee} \leq \tau_p$
- Bohm velocity for the multicomponent plasma (Pb, Ba, Ti, O):

$$V_B = \sqrt{\sum_q \frac{n_q}{n_e} C_q^2}$$

❑ A. M. Hala and N. Hershkowitz, *Rev. Sci. Instrum.* **72**, 2279 (2001).

- Thickness of the unipolar sheath:

$$h_s(t)\left(1+\frac{12\pi h_s(t)}{125\lambda}\right)^{1/4} = \lambda_D(t)\left(\sqrt{2Y}\left(\frac{Y}{3}+2\right)-1.8197\right); \quad Y=\sqrt{1+2\frac{e\varphi(t)}{kT_e}}-2$$

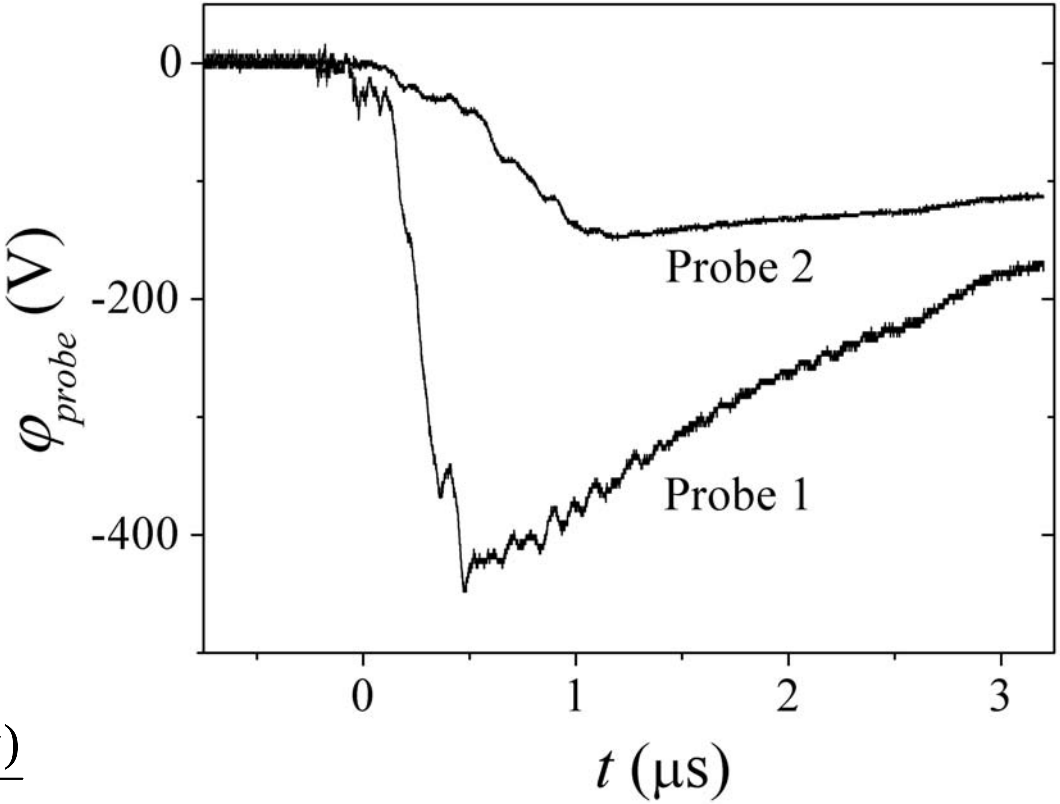
❑ K. U. Riemann and L. Tsendin, *J. Appl. Phys.* **90**, 5487 (2001)

Floating probes in expanding plasma

At C ~ 25 pF observed signals are in the range of hundreds of volts => much higher than noise.

Plasma density $n_i(x,t)$ can be obtained from:

$$\frac{d}{dt}\varphi(t) = \frac{i(t)}{C} = \frac{0.52Zen_i(t)V_B S(t)}{C}$$

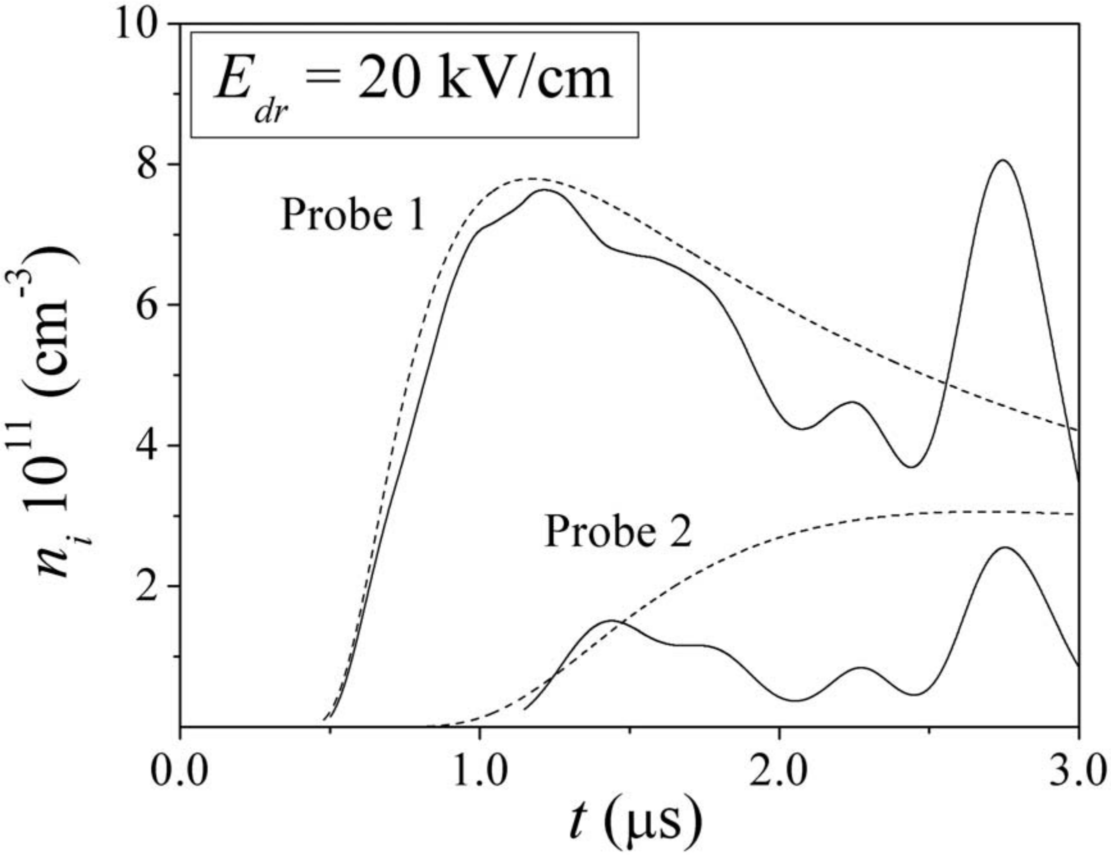


- ❑ A. Dunaevsky and N. J. Fisch, *J. Appl. Phys*. **95**, 4621 (2004)

Fit of the density profiles

Varying n_0, and T_{e0}, experimentally observed profiles can be fitted by the self-similar solution.

Discrepancy on the second profile: 1D approximation is not valid: source width is less than the distance to the second probe



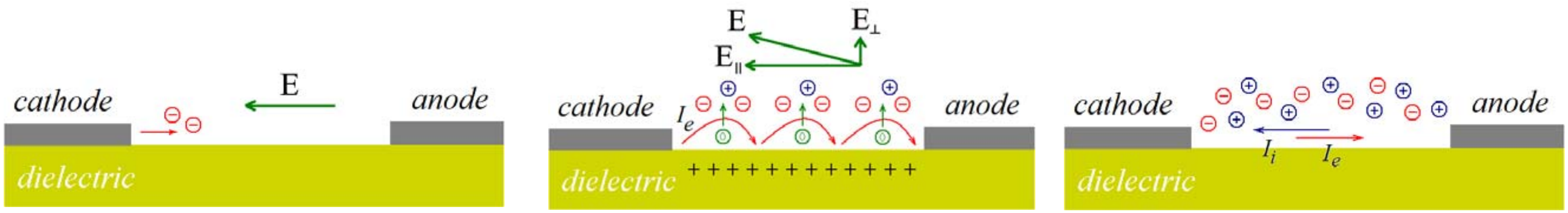
Intermediate stage of surface discharge

Surface discharge in vacuum begins from the electron avalanche driven by secondary electron emission, and ends by the arc. Intermediate stage of the formation of plasma bridge between electrodes depends strongly on material properties and poorly understood.

❑ H. C. Miller, *Phys. IEEE Trans. Electr. Insul.* **24**, 765 (1989).

Importance:

- prediction of the insulating properties of materials
- surface discharge plasma sources



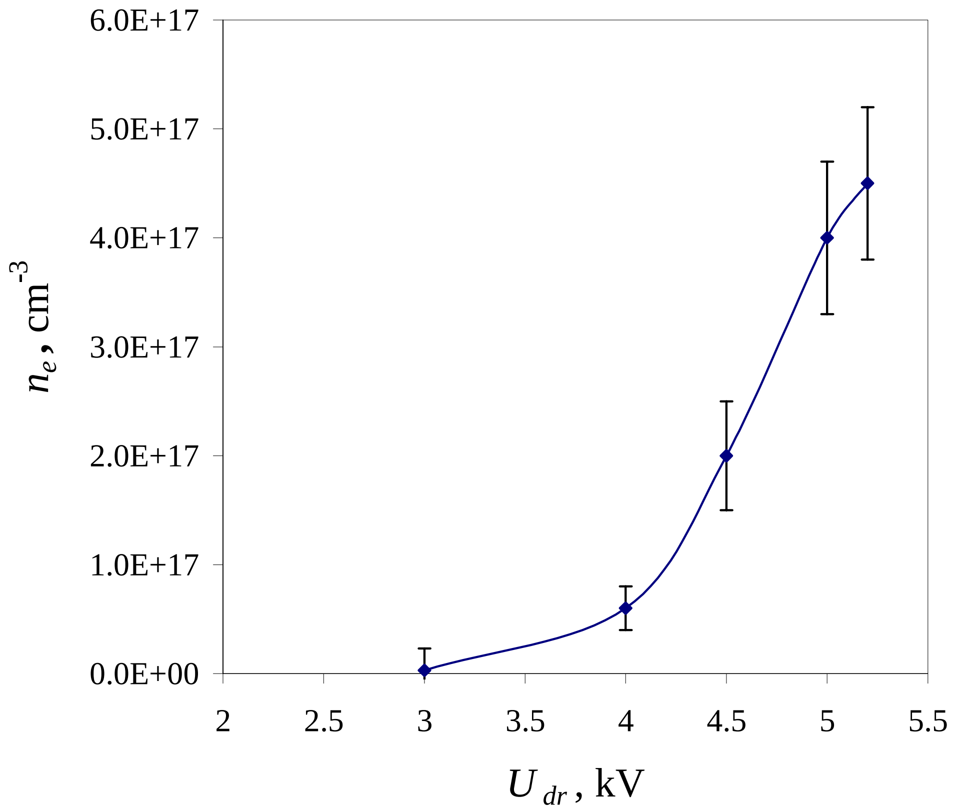
❑ H. Boersch, H. Hamisch, and W. Ehrlich, *Z. Angew. Phys.* **15**, 518 (1963).

Initial electron density

Plasma density at the vicinity of the surface grows as ~ $U^{3/2}$ for the driving electric fields of 16 – 30 kV/cm.

Measured density coincides well with the only experimental evidence measured by deflection of a laser beam:

$n_{e0} \sim 10^{17}$ - 10^{18} cm^{-3}



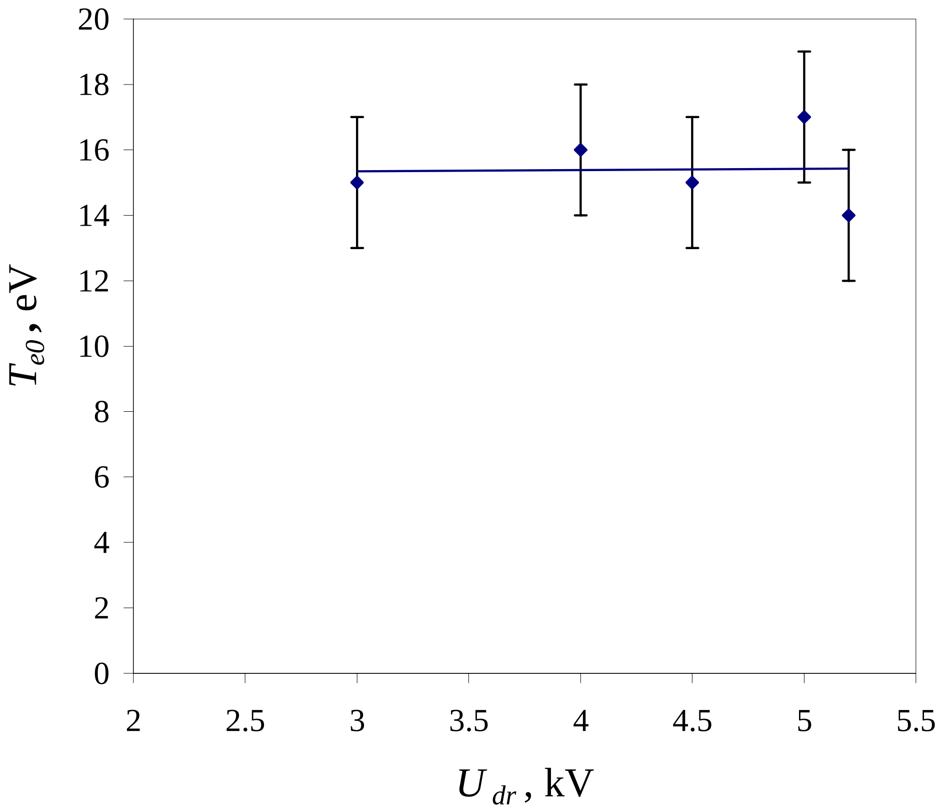
- ☐ G. Masten, T. Muller, F. Hegeler, and H. Krompholz, *IEEE. Trans. Plasma Sci*. **22**, 1034 (1994)

Efficient electron temperature

Initial "efficient" electron temperature corresponds to the average energy of electrons in the avalanche. This energy, in its turn, is determined by the energy of the first crossover ζ_1 of the yield of secondary electron emission and does not depend on the applied electric field:

$T_{e0} \sim 0.5\ \zeta_1$

For PZT ceramics used in the experiments, $\zeta_1 \sim 25$ eV



T_{e0} and n_{e0} does not appear at the same time! The method does not resolve chain of processes.

Conclusions

• Measurements in expanding plasmas may resolve important features which are hidden by the small size and short duration of the process: study of the surface discharge is a good example

• Simple probe diagnostics can be used

• Reliable 3D kinetic theory of adiabatic expansion of plasma bunches with arbitrary initial EEDF is required. First attempt (self-similar solution):

❑ V. F. Kovalev and V. Yu. Bychenkov, *Phys. Rev. Lett.* **90**, 185004 (2003)