Simulation of Plasma Decay in Capillary Discharges

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Outline

- Introduction.
  Electron beam transportation experiments

- Simulation of long lived axial motion of capillary plasma after current pulse

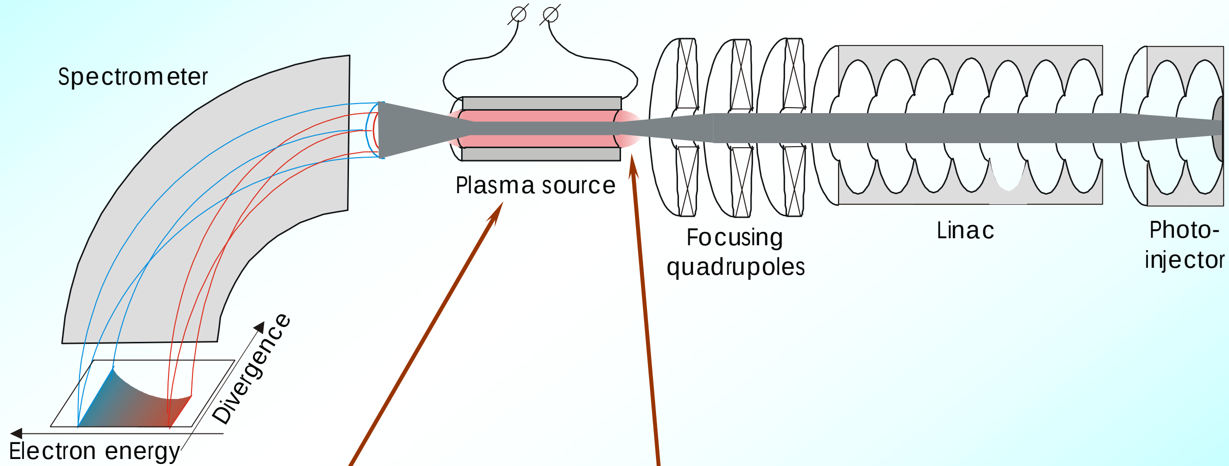
- Scaling of parameters of capillary plasma in ablative capillary discharges
  and
  its lower limit

- Conclusions

Cohesive Acceleration and Focusing of Relativistic Electrons in Plasma of Capillary Discharge

V. Yakimenko, I.V. Pogorelsky *et al*. PRL (2003) to be published

Experiment at Accelerator Test Facility, Brookhaven National Laboratory

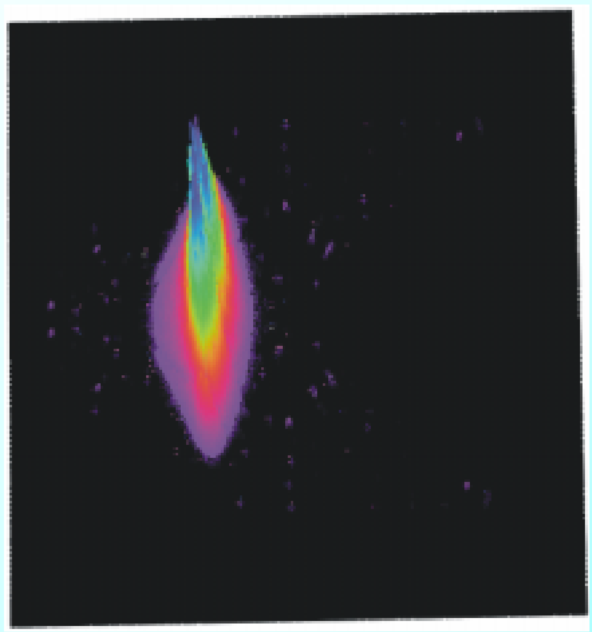


polypropylene capillary
17 mm long and 1 mm inner diameter
~ 300 A; $t_{1/2}$ ~ 300 ns

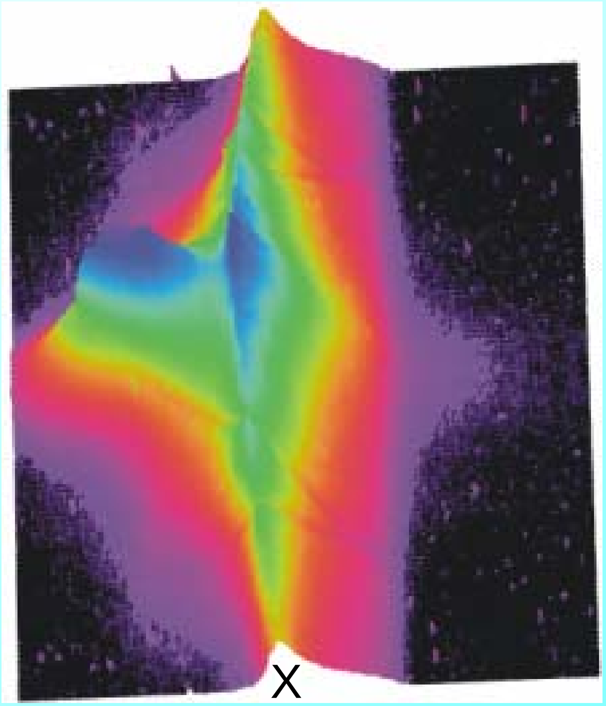
60 MeV, 300 pC, 1.5 ps long electron beam is focused to spot size of ~100 mm

Cohesive Acceleration and Focusing of Relativistic Electrons in Plasma of Capillary Discharge

No current pulse



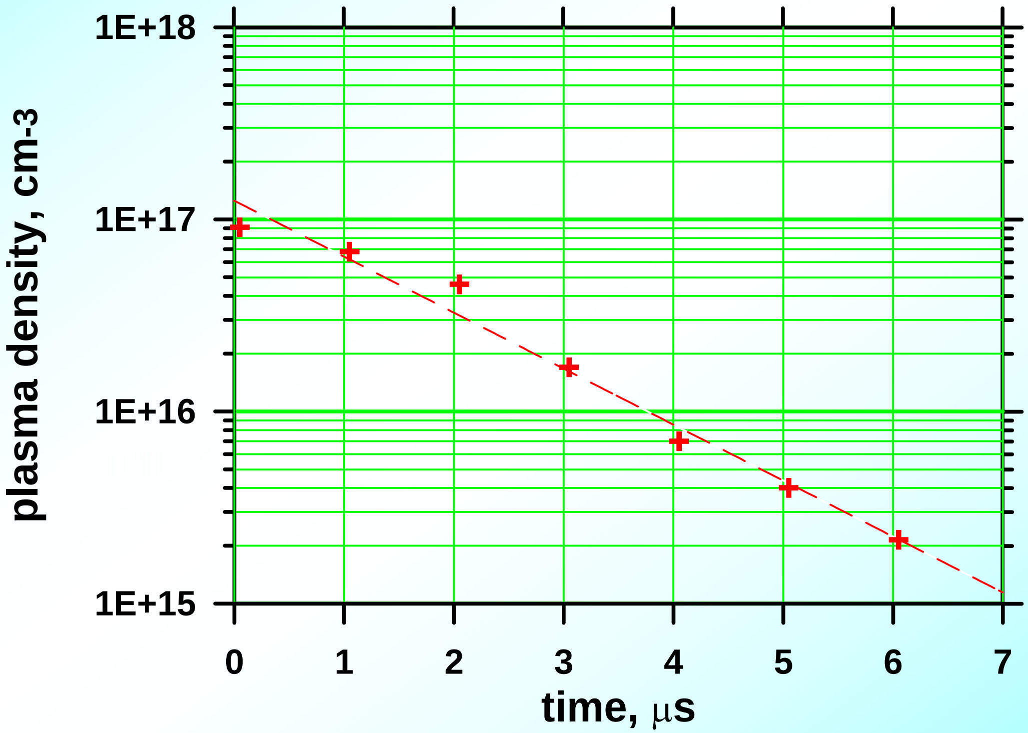
With current pulse, at $t = 3\ \mu s$



focusing wakefield, 35 MV/m

Cohesive Acceleration and Focusing of Relativistic Electrons in Plasma of Capillary Discharge

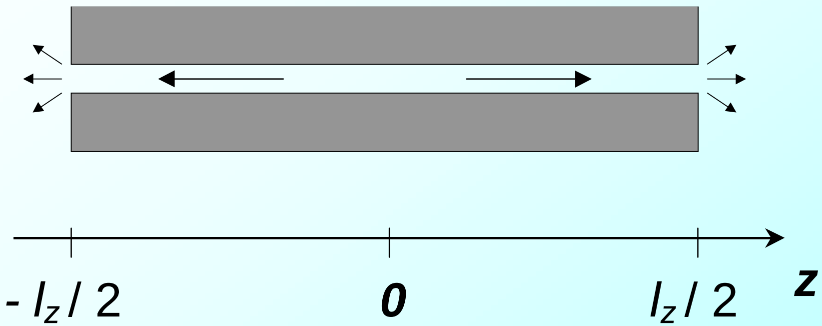
Processing of the previous data gives the following $N_e(t)$:



Why does the plasma decay so quick?

- Though recombination rate is high enough, cooling of the plasma on relatively cold walls demands much longer time. Thermal conduction is not so effective.
- Hydrogen filled noablative ceramic capillary discharge [D. J. Spence *et al*., PRE **63**, 015401 (2001)], was considered in the paper by N. Bobrova *et al*. [PRE, **65**, 016407 (2001)]. The hydrogen plasma was in thermal and mechanical quasi steady state. Thus all plasma parameters were functions of current values of electric current and plasma mass per length. As a result outflowing of plasma from capillary ends leads to exponential decay of plasma density.
- If the plasma would be an ideal gas then adiabatic outflowing will follow an power low decay: $n(t) \propto 1/t^3$.
- However for partially ionized plasma with z ~ 1, energy of ionization is considerably higher than energy of thermal motion of plasma particles, so that the ionization energy may play a role of effective thermostat.
- Hence such plasma may show an exponential like decay even in the adiabatic case.

Axial Motion of Capillary Plasma after Terminating of Current Pulse



$$\rho\left(\partial_t + v\partial_z\right)v = -\partial_z\left(p_e + p_i\right);$$
$$\partial_t\rho + \partial_z\left(\rho v\right) = 0;$$
$$\rho\left(\partial_t + v\partial_z\right)\varepsilon_e + p_e\partial_z v = C_{ei}\left(T_i - T_e\right);$$
$$\rho\left(\partial_t + v\partial_z\right)\varepsilon_i + p_i\partial_z v = C_{ei}\left(T_e - T_i\right).$$
$$\varepsilon_e = \varepsilon_e\left(\rho, T_e\right); \quad p_e = p_e\left(\rho, T_e\right);$$
$$\varepsilon_i = \varepsilon_i\left(\rho, T_i\right); \quad p_i = p_i\left(\rho, T_i\right).$$
$$v\Big|_{z=\pm l_z/2} = \pm c_s$$

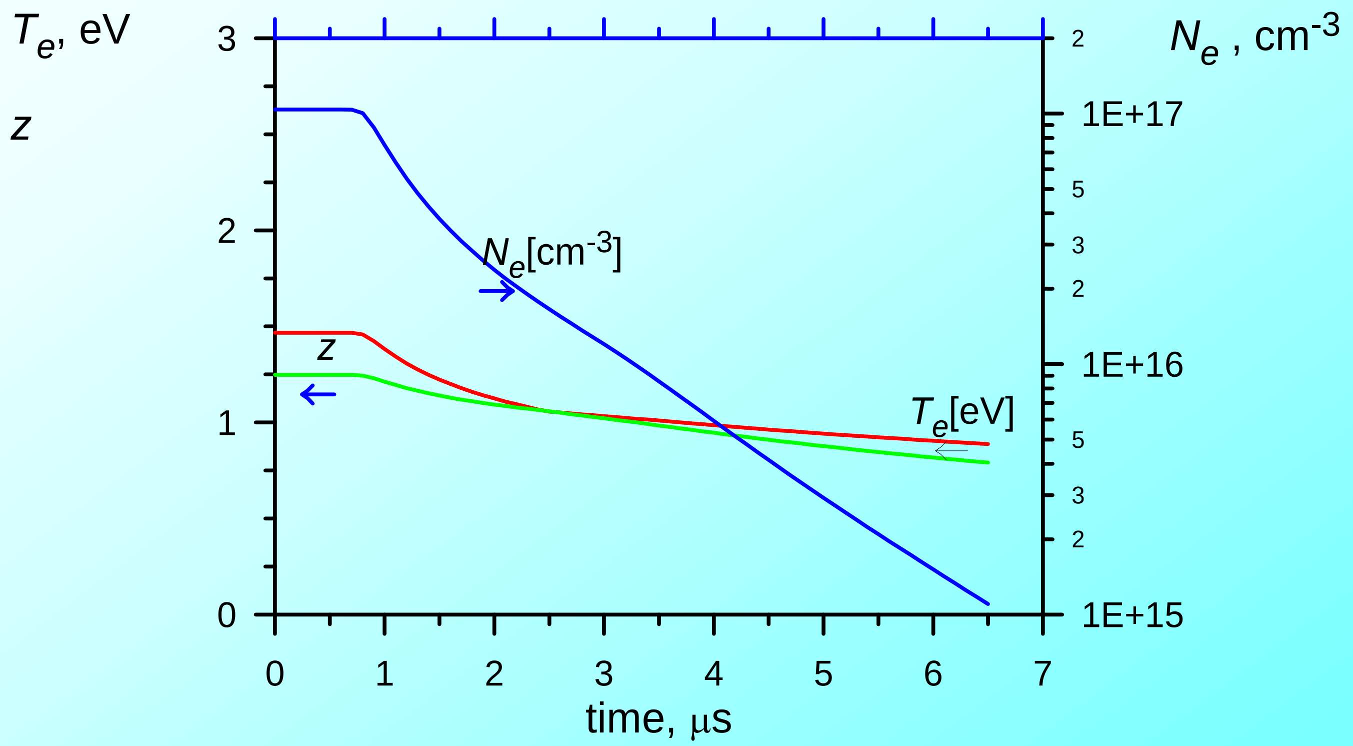
NPINCH updated

$T_{ei}(t = 0) = 1.47$ eV

$\rho_{CH2}(t = 0) = 0.586\ \mu g/cm^3$

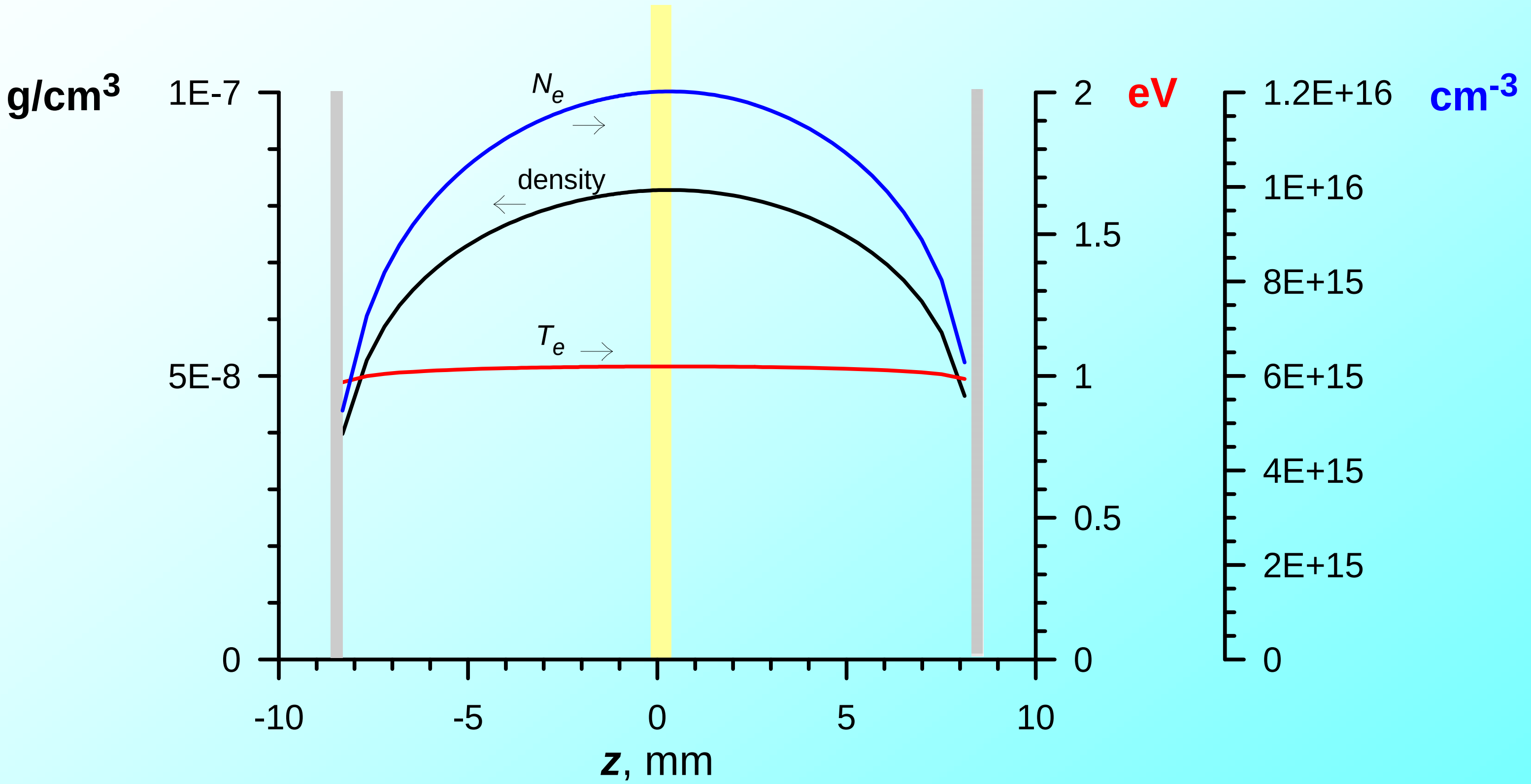
Results of the Simulation of Axial Motion of Capillary Plasma

Time dependence of plasma parameters at the middle of the capillary

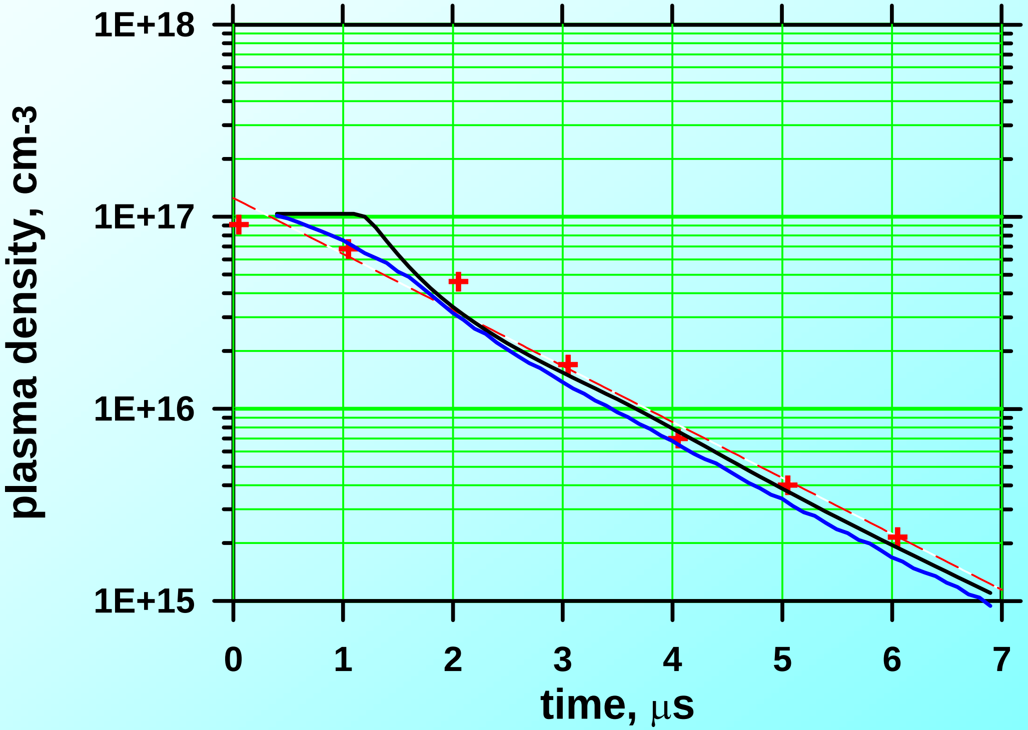


Results of the Simulation of Axial Motion of Capillary Plasma

Axial distributions of plasma parameters at t = 3 μs



Comparison of Results of the Simulation with the Experimental Data



Preliminary Conclusions

- main process governing plasma parameters evolution in such experiments is outflowing of plasma from the ends of the capillary
- plasma cooling due to its contact with relatively cold walls and recombination caused by this cooling play negligible roles
- reasonable coincidence of simulation and experimental data gives more confidence in this indirect method of plasma density measurements
- Next Question:

  What processes determine capillary plasma parameters during the main current pulse?

Plasma Density in Ablative Capillary Discharges

- For sufficiently high energy flux from the capillary plasma toward the capillary walls and for sufficiently soft material the "bottle neck" for the process of plasma formation is transport of necessary heat from the relatively hot plasma in the bulk of discharge toward relatively cold low ionized wall plasma and not process of phase transition from the solid wall material to its vapor.

- This assumption is valid for:
  • the Rocca type gas filled plastic capillaries
  (10…40… kA; duration of several tens of ns; diameter of few mm).
  • the Zigler type purely ablative plastic capillaries
  (500 A … 2 kA ..., sub microseconds duration;
  diameter of 200…800 μm)
  • the Kunze type ablative capillary
  •(10…20 kA; duration of several hundreds of ns; diameter of few mm).

- This assumption may be invalid. An example is hydrogen filled ceramic capillaries: Hooker *et al.* PRL, **63**, 015401(R) (2000)
  [300 A; 200 ns; 300 μm]

Plasma Density in Well Ablative Capillary Discharges

- Plasma-wall interaction and wall ablation in well ablative capillary discharges can be easily simulated if we will treat the wall as a gas of condensed matter density.

- MHD simulations of capillary discharges with such “boundary conditions” at the walls gave the following scaling for plasma density (D. Kaganovich, P. Sasorov, C. Cohen, A. Zigler. Appl. Ph. Lett., 75, 772 (1999)):

$$N_e(t = 200\,\mathrm{ns}) = 8.5 \cdot 10^{16}\,\mathrm{cm}^{-3}\, I_{m\,\mathrm{kA}}^{1.2}\, R_{c\,\mathrm{mm}}^{-3.2}$$

  for glass capillary.
  This scaling was checked for glass capillaries with I_m = 0.5 - 1.5 kA and 300-800 μm diameters.

- Both this scaling and direct simulation of the Brookhaven capillary show plasma density several times more than measured density.

- It means that plasma ablation in such capillaries (plastic; 1 mm diameter; 300 A; 400 ns) is limited by the process of solid-gas phase transition, that can be hardly described by the hydrodynamic approach.

Simulation of the Initial Stage of the Brookhaven Capillary Discharge

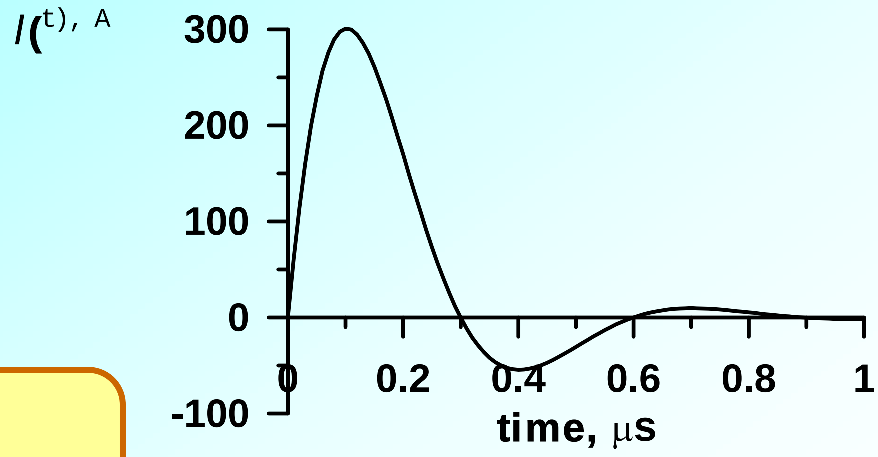
- We have no tools for full simulation of ablative capillary discharge when the ablation is limited by the phase transition rate.
- Instead of full simulation the discharge was simulated by neglecting of the ablation at all and by choosing of the initial plasma density so that the simulation would reproduce measured electron density.

$\rho_{CH2}(t = 0) = 0.9\ \mu g\ cm^{-3}$

$T_e(t = 0) = 1$ eV

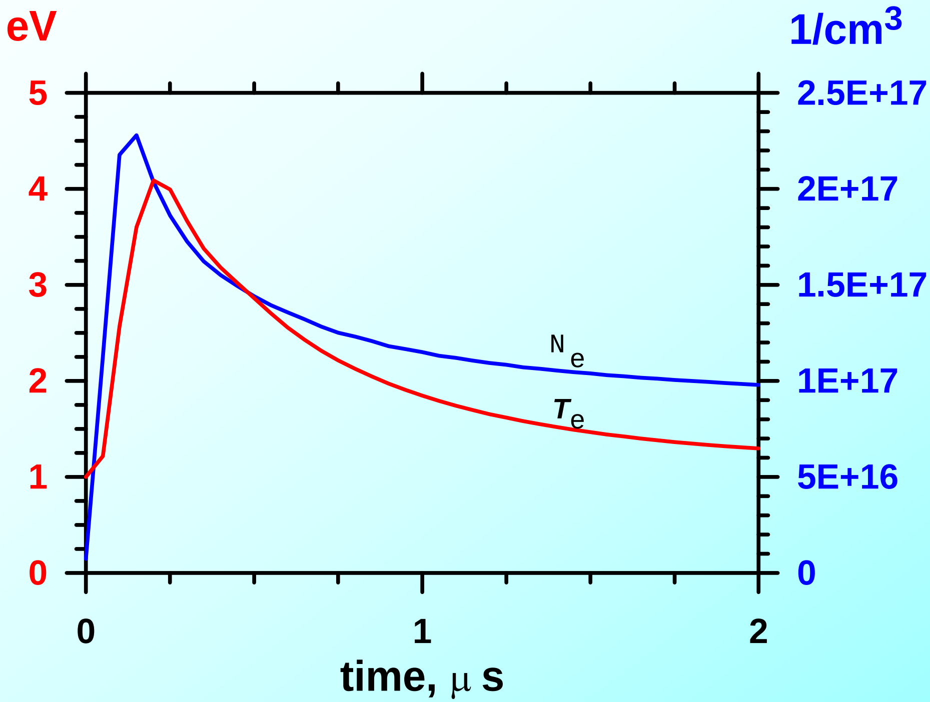
diam = 1 mm

Full 1d (r,t) MHD simulation with necessary boundary conditions at the cold walls.

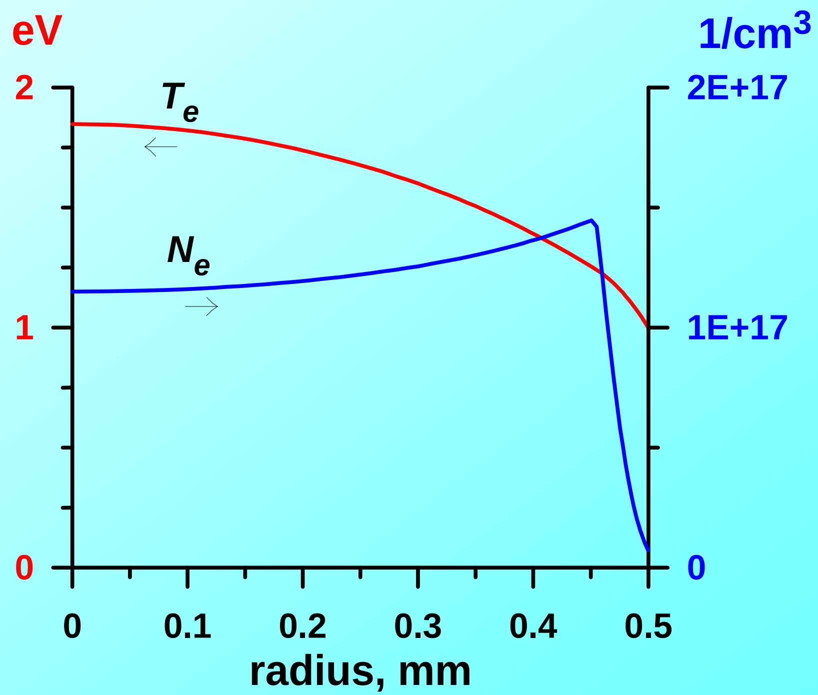


Results of the Simulation of the Initial Stage of the Brookhaven Capillary Discharge

Dependence of plasma parameters at the axis on time



Radial distribution of plasma parameters at t = 1 μs



Conclusions

- Probing of capillary plasma by high energy beams is quite effective tool for investigation of such plasma:
  - Heavy ion beam was used in ITEP by Golubev *et al*. (~1998…2000).
  - Relativistic electron beam was used by V. Yakimenko, I.V. Pogorelsky *et al*. [PRL, 2003] in Oxford University

- Low current ablative discharge in plastic capillary may produce a low density plasma for guiding of CO_2 laser pulses owing to the ablation is limited by the phase transition in this case.

- Plasma axial outflowing is an additional, well controlled way to produce such low density plasma.