ON THE GENERATION AND DISRUPTION OF A PICOSECOND RUNAWAY ELECTRON BEAM IN AIR AT STRONG OVERVOLTAGE

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OUTLINE

- INTRODUCTION
- EXPERIMENTAL and MODELING RESULTS

- STREAMER FORMATION
- ELECTRON EMISSION and IONIZATION SIMULATION
- BEAM-PLASMA INSTABILITIES

- SUMMARY

experimental review:

G. A. Mesyats, M. I. Yalandin, A. G. Reutova, K. A. Sharypov, V. G. Shpak and S. A. Shunailov "Picosecond runaway electron beams in air" *Plas. Phys. Rep.* **38** 29 (2012)

theory:

S. A. Barengolts, G. A. Mesyats, M. M. Tsventoukh, and I. V. Uimanov, *Appl. Phys. Lett.* **100**, 134102 (2012)

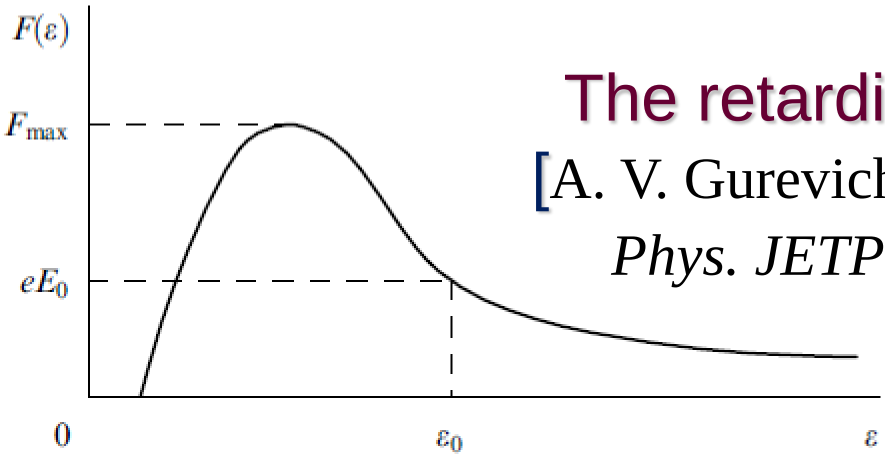
INTRODUCTION

Runaway regime of the acceleration implies that particle gain more energy from field than can be dissipated by collisions

$$m\frac{dv}{dt} = eE - F_d \geq 0$$

Rough estimation for 1 atm

$$F_d \sim \frac{10\,\text{eV}}{1\mu\,\text{m}} = 100\,\frac{\text{keV}}{\text{cm}}$$



The retarding force

[A. V. Gurevich, 1961 *Sov. Phys. JETP* **12** 904]

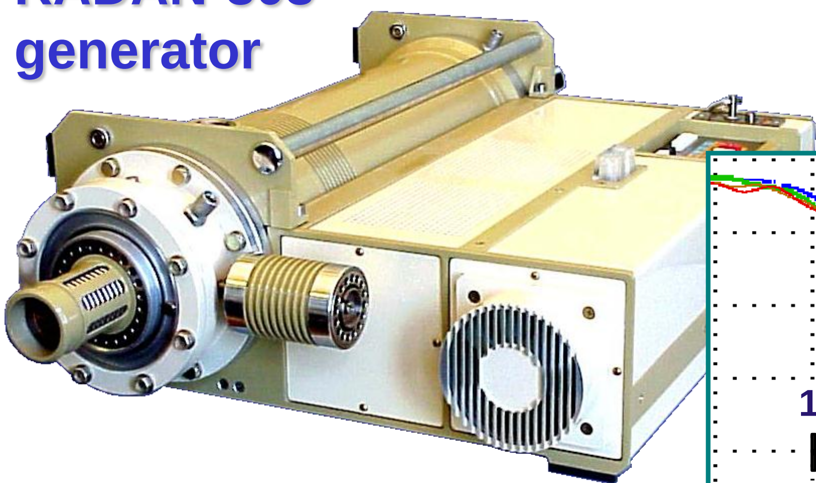
$$F_{d,Bethe} = \frac{2\pi e^4 Z}{\varepsilon} n \ln\frac{\varepsilon}{I}$$

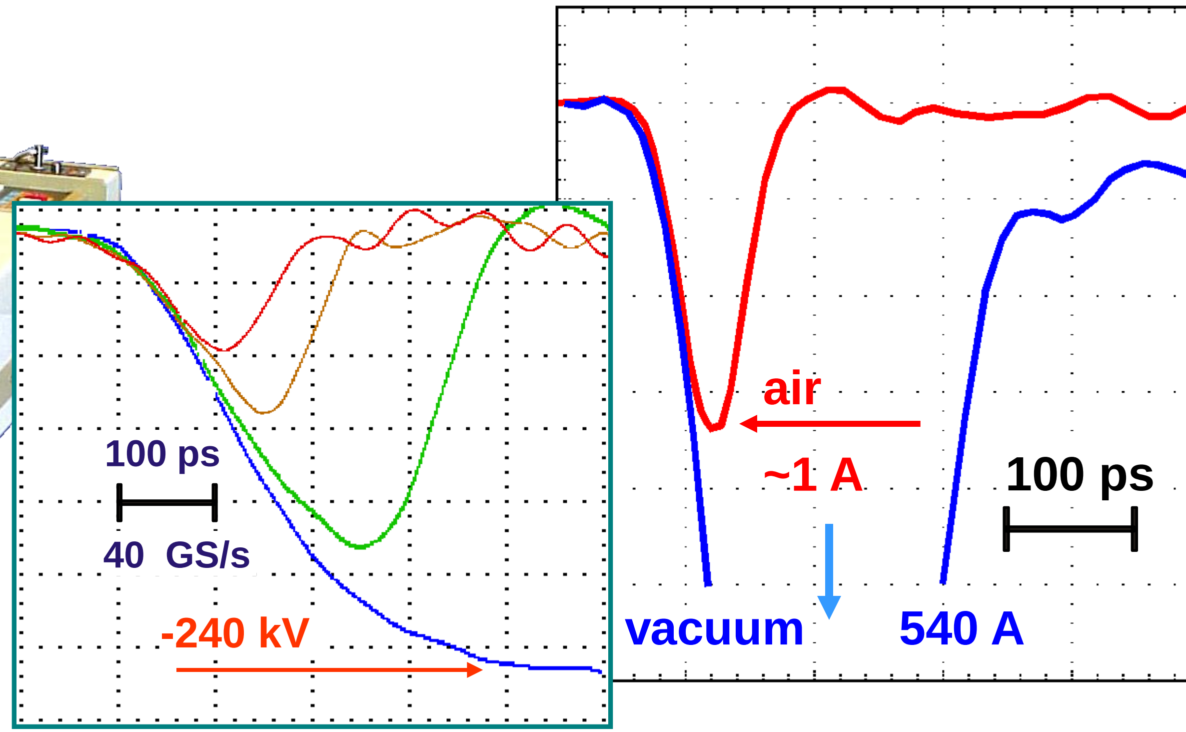
Observation of x-ray emission from the runaway electrons in pulsed nanosecond high-pressure discharge [Mesyats G A, Bychkov Yu I, Kremnev V V 1972 *Sov. Phys. Usp.* **15** 282]

PICOSECOND DISCHARGE

A considerable advance has been made recently in the development of small-sized picosecond pulsed power supplies [G. A. Mesyats, M. I. Yalandin *Phys. Usp.* **48** 211 (2005)]

RADAN-303 generator

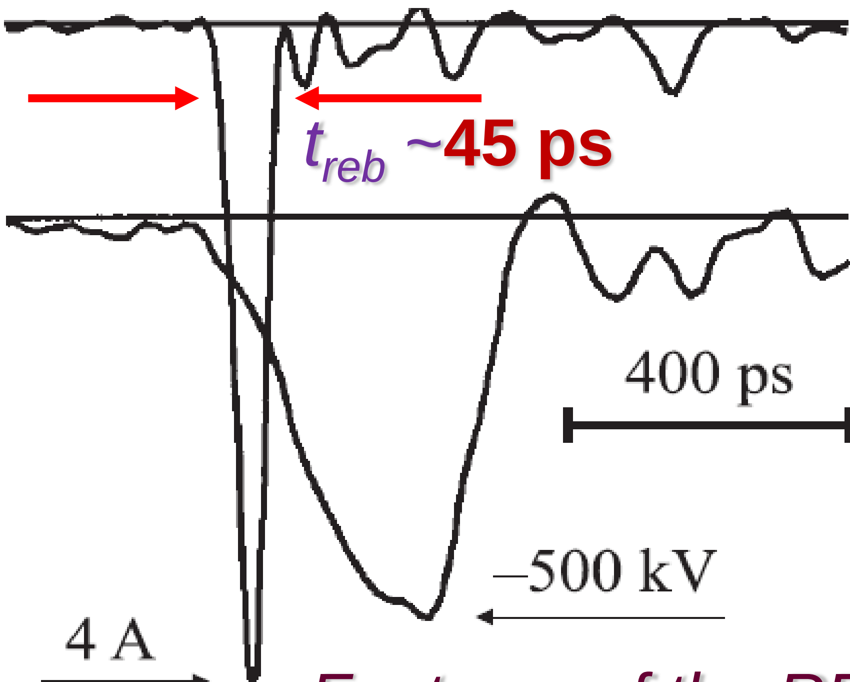


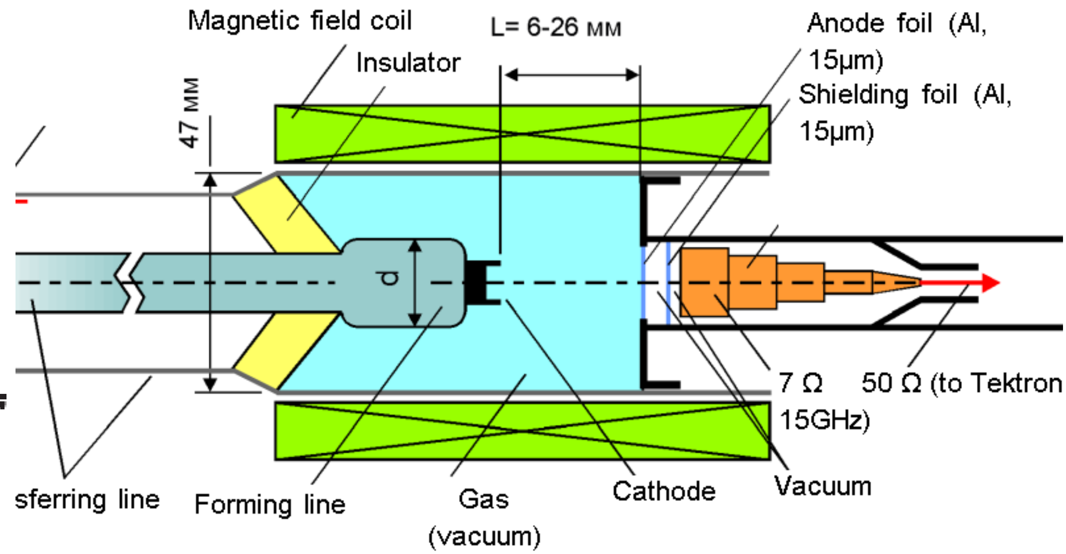


Advantage was taken of these power supplies and techniques for diagnosing fast processes to perform a detailed experimental study of the runaway electron beams (REBs) generated during breakdowns in atmospheric-pressure gas-filled diodes

EXPERIMENT

Generation of runaway electron beams, **REB, (I_{reb} up to 10 A)** in dense gases at strong overvoltage (E < **1.5 MV/cm,** ***dU/dt*** **~ 2 MV/ns**)





G.A.Mesyats, V.G.Shpak, S.A.Shunailov, M.I.Yalandin, *Tech. Phys. Lett.* 34 169 (2008)

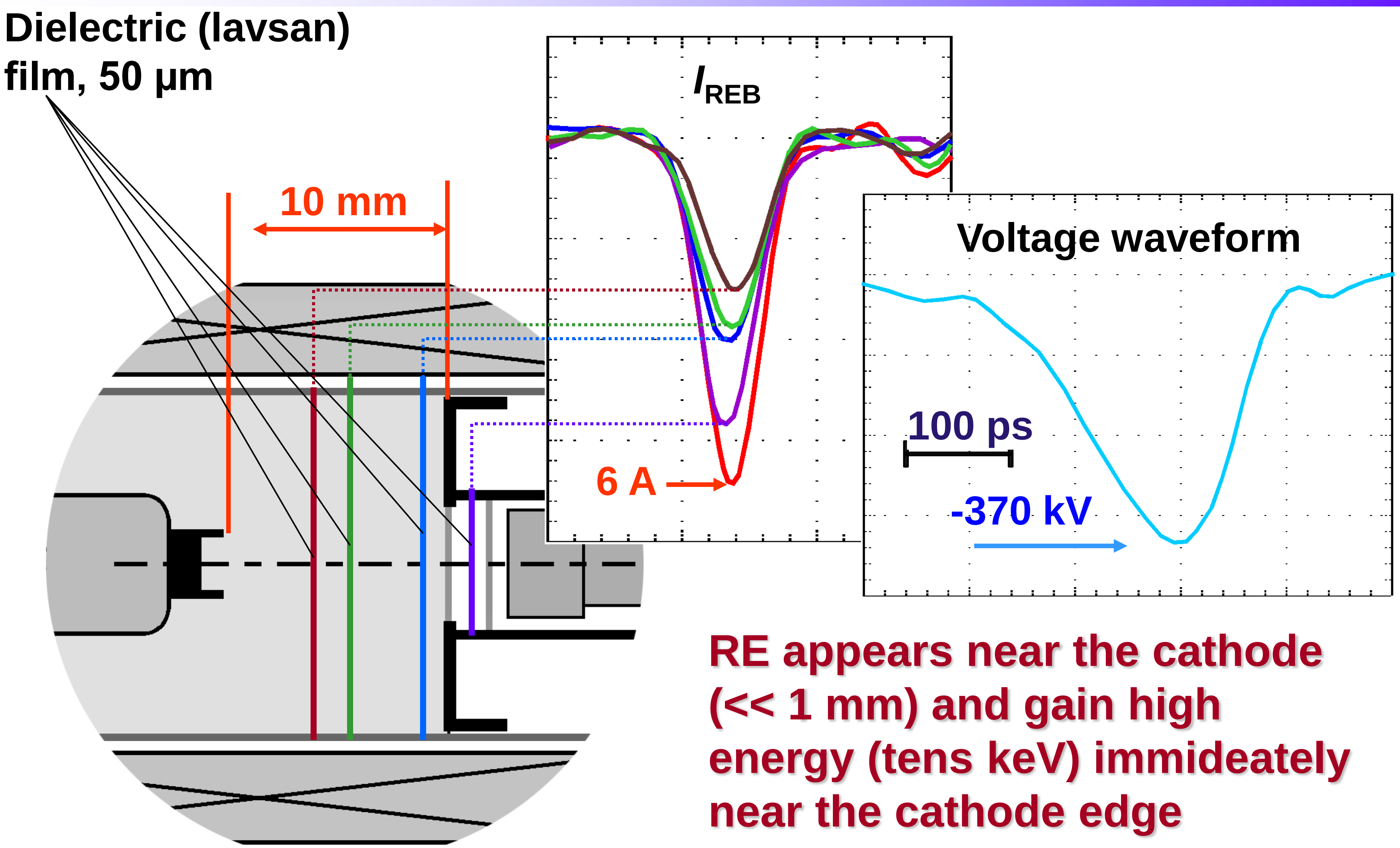
G.A.Mesyats, S.D.Korovin, K.A.Sharypov, V.G.Shpak, S.A.Shunailov, M.I.Yalandin, *Tech. Phys. Lett.* 32 18 (2006)

M. I. Yalandin, G. A. Mesyats, A. G. Reutova, K. A. Sharypov, V. G. Shpak and S. A. Shunailov, *Tech. Phys. Lett.* 37 371 (2011)

Features of the REB

- **Short duration ($t_{reb} << t_{pulse} \sim t_{eb,vacuum}$)**
- **REB current amplitude ($I_{reb} << I_{eb,vacuum}$ < 10 kA)**

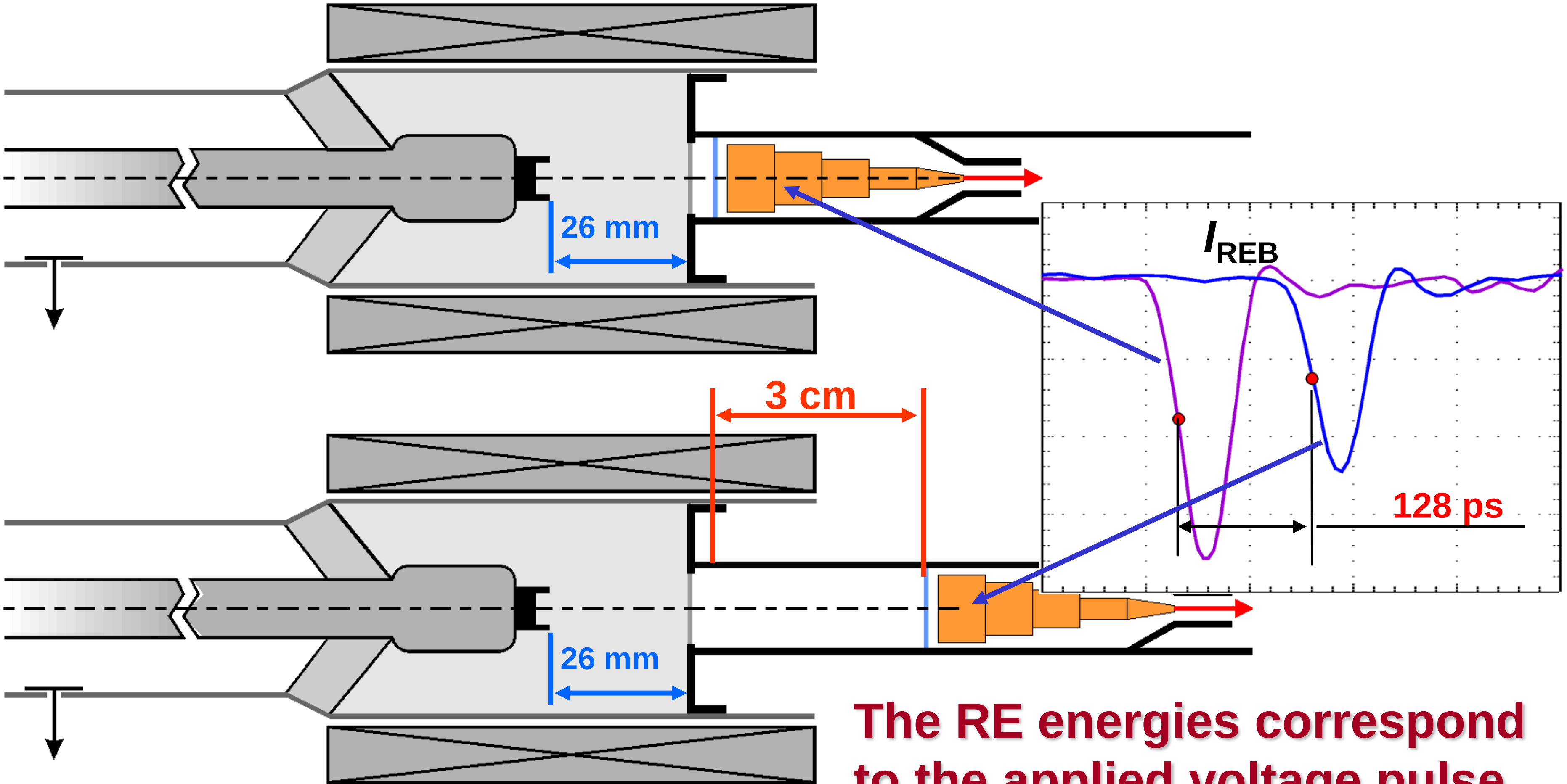
REB appearance region



RE appears near the cathode (<< 1 mm) and gain high energy (tens keV) immideately near the cathode edge

M. I. Yalandin 2009 Lebedev Inst.

TIME OF FLIGHT MEASUREMENTS



The RE energies correspond to the applied voltage pulse eU_{pulse}, like for the acceleration in vacuum

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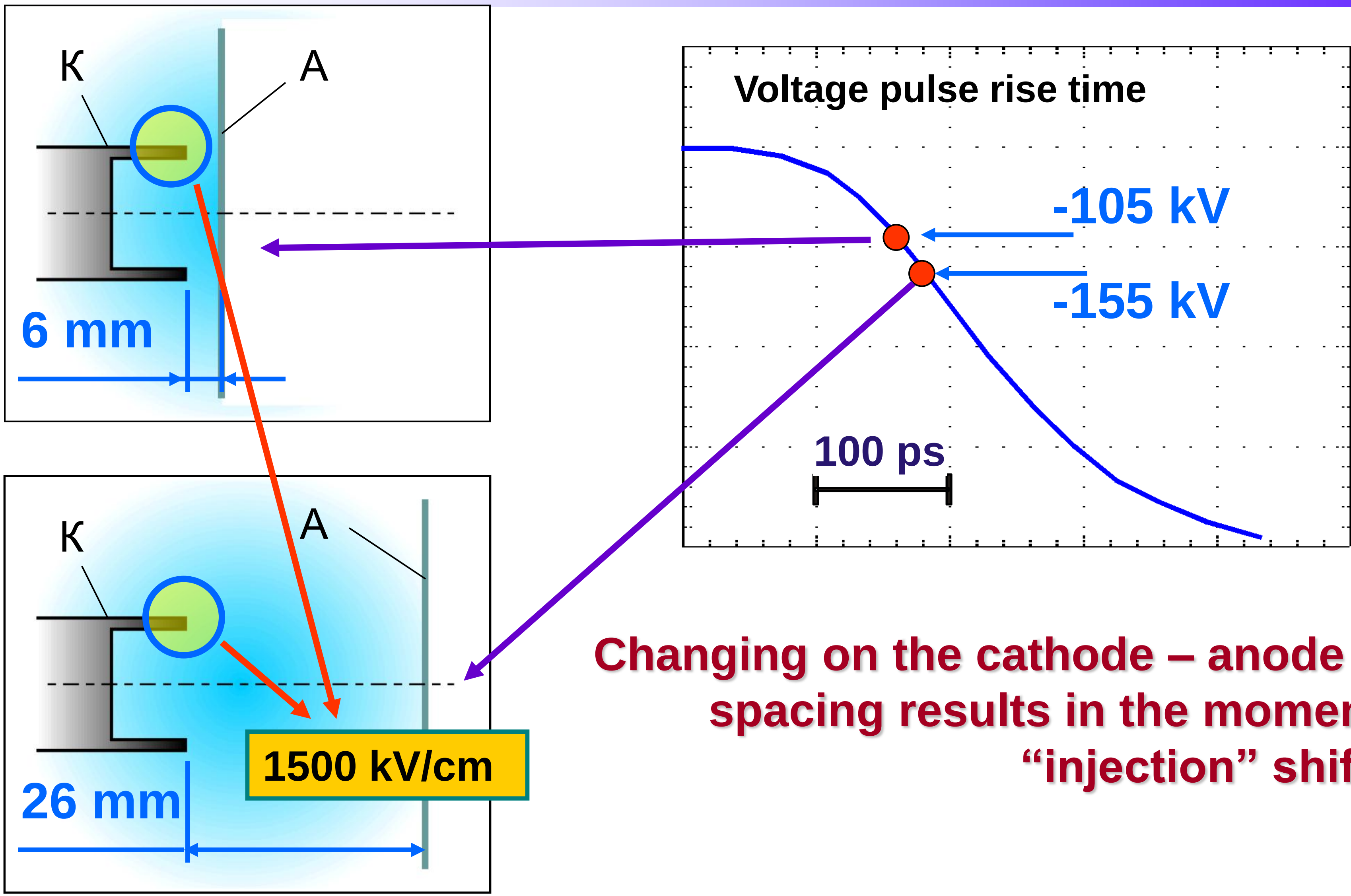
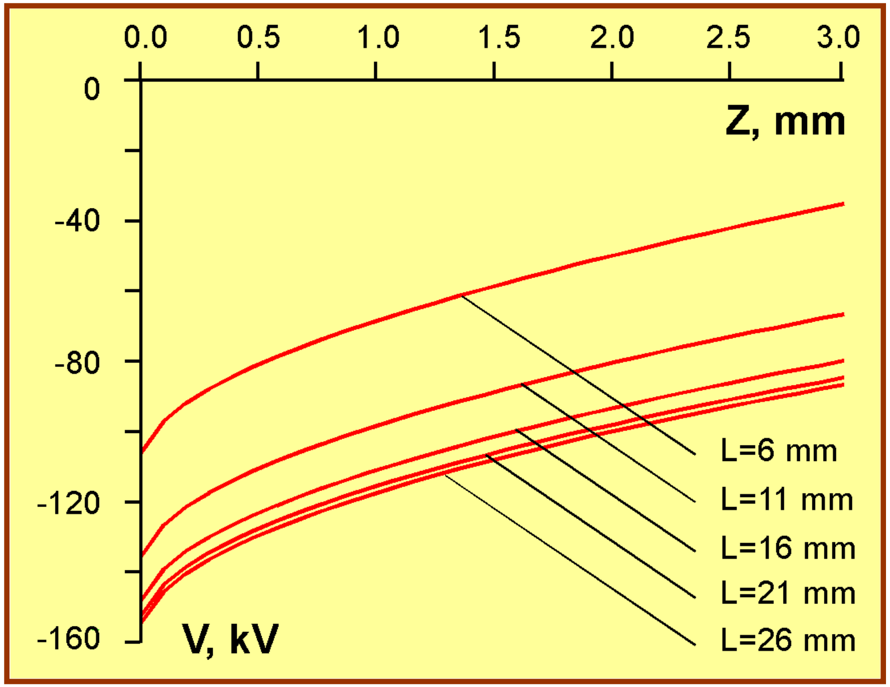
MOMENT OF REB "INJECTION"

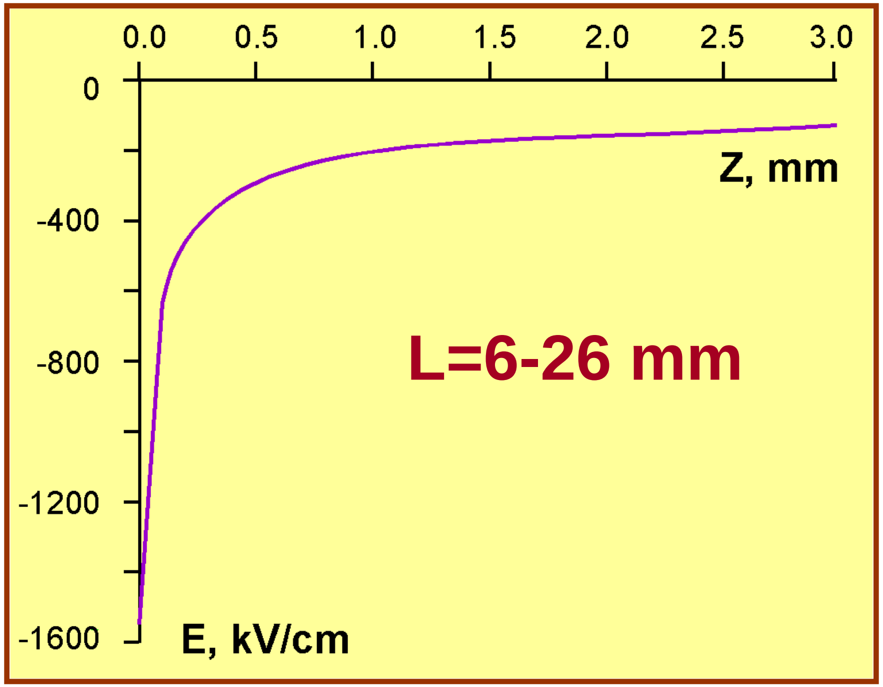


Changing on the cathode – anode gap spacing results in the moment of "injection" shifting

Vacuum field calculations and REB



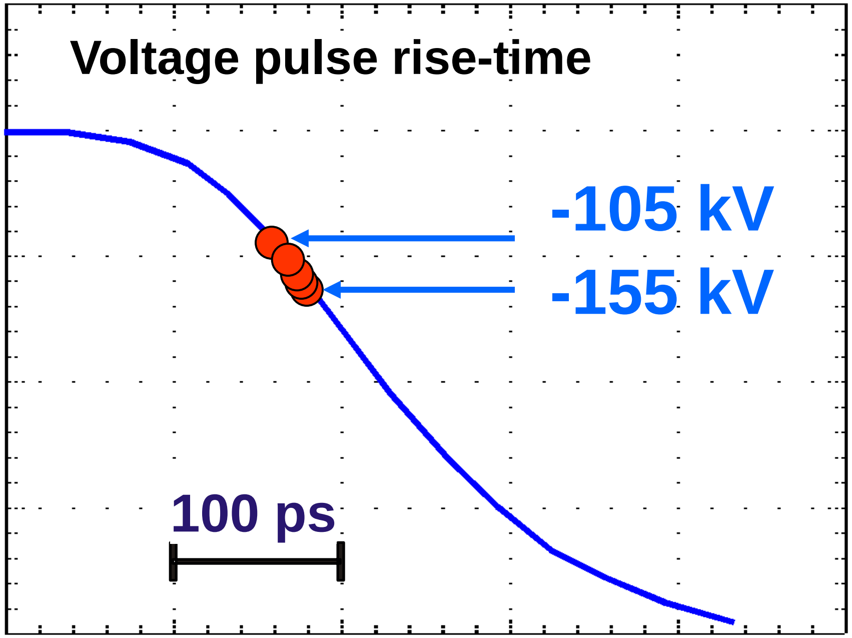
U(z)

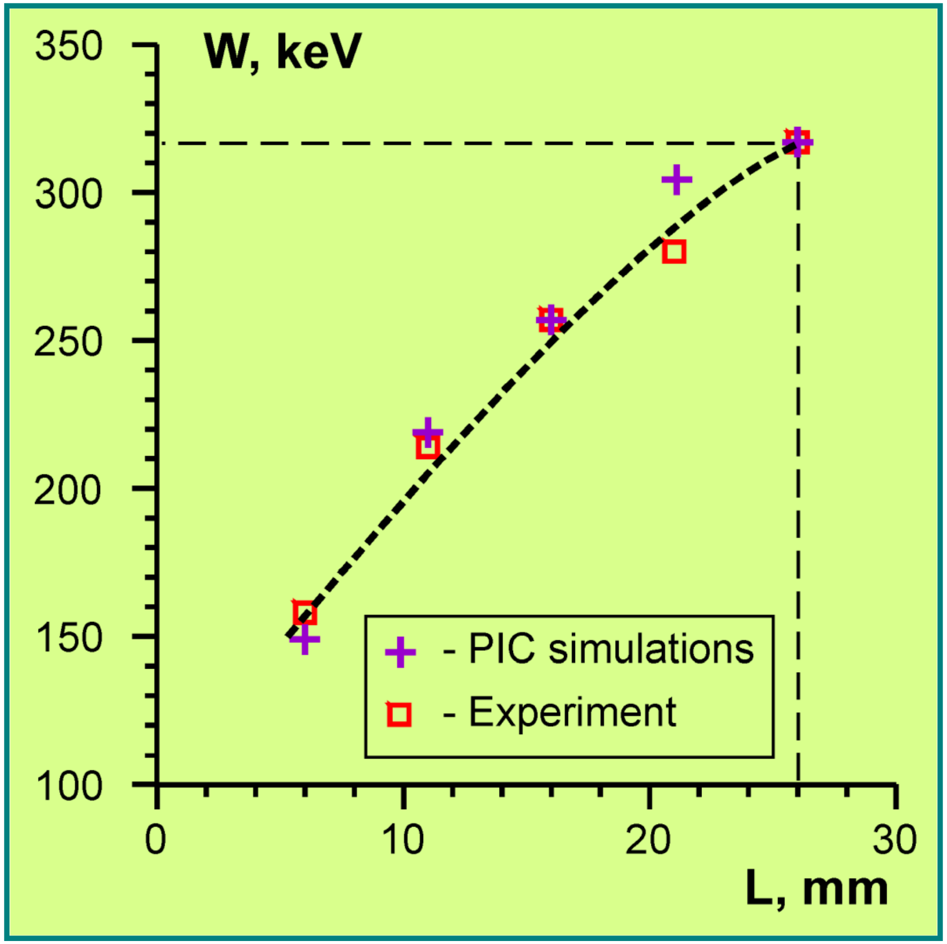


E(z)

Vacuum field calculation indicates that REBs are generated as the electric field at the cathode reaches some threshold value ~1.55 MV/cm independent of the electrode separation

REB acceleration mode





At the threshold field *E*~1500 kV/cm the measured electron energy coincides with the vacuum calculations

RUNAWAY CONDITIONS

The magnitude of $E_{cr} = \max F_d(\varepsilon)$ can be estimated more exactly by using the well-known Bethe formula and the experimental dependences [L. R. Peterson and A. E. S. Green, *J. Phys. B: At. Mol. Phys.* **1** 1131 (1968)**]**

kV/cm	N_2	H_2	He
$E_{cr,\ Bethe}$	**450**	**180**	**117**
$E_{cr,\ Peterson\text{-}Green}$	**270**	**108**	**54**

Recall that at $E < E_{cr}$ the runaway mode arises for high-energy electrons

[A. V. Gurevich, 1961 *Sov. Phys. JETP* **12** 904]

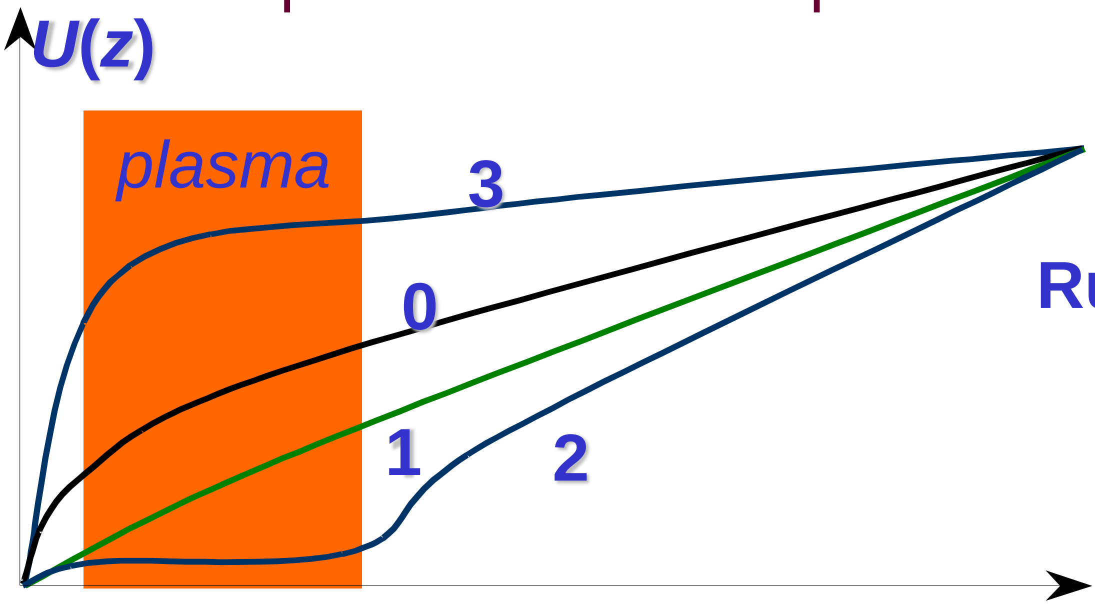
$$\frac{\tau_{reb}}{\tau_{coll}} \approx \left(\frac{E_{cr0}}{E}\right)^{\frac{3}{2}}$$

It is clear that the REB threshold electric field, $E_{0thr} \approx$ 1.55 MV/cm is substantially greater than even the highest estimated critical field

PLASMA APPEARANCE

The gap bridging and U_{pulse} decreasing does not occurs within t_{REB} ≈45 ps. This has been confirmed by time-of-flight measurements, demonstrating a "vacuum-like" REB acceleration mode

Thus, even the average electric field during the main pulse <*E*> being of about 100 kV/cm that is only a few times lower than maximal of E_{cr}, whereas for a guaranteed runaway prevention it is required for *E* to be << E_{cr}



Runaway in a plasma :

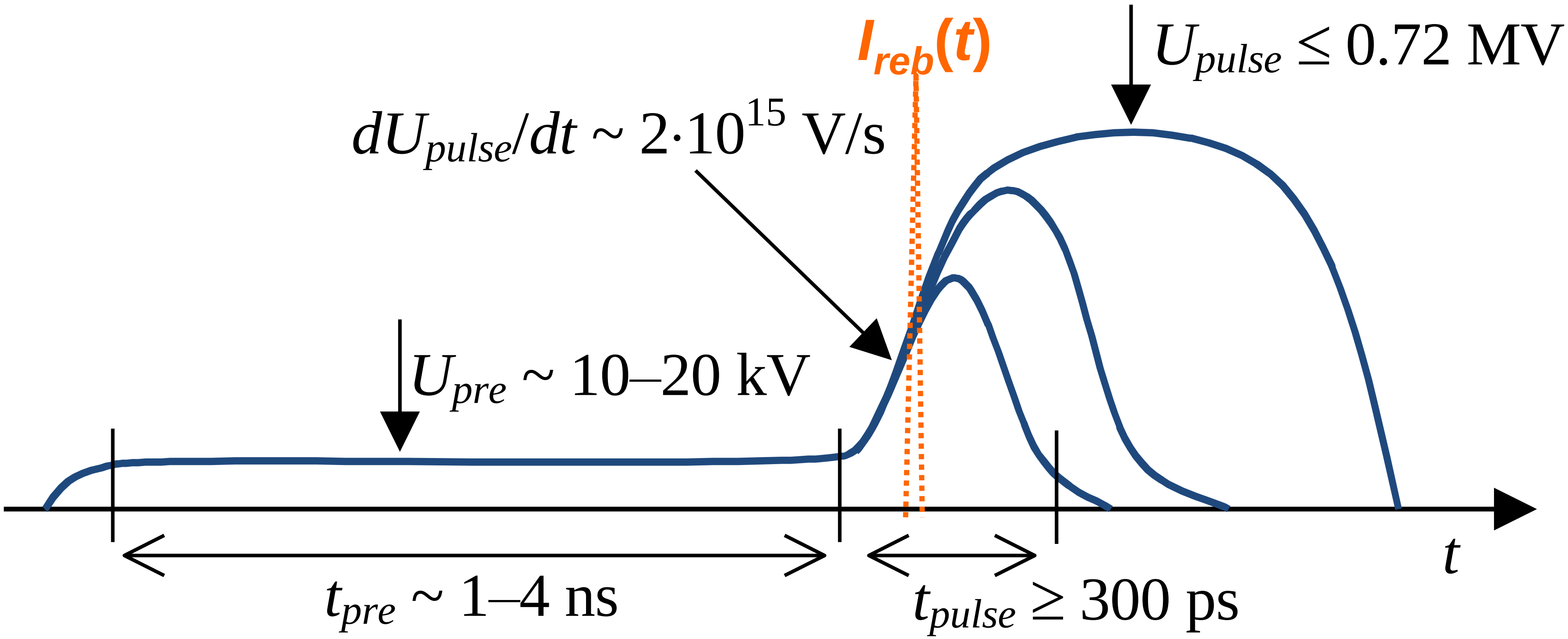
$$E_{cr,pl} \approx 0.214\Lambda \frac{e}{L_D^2} \sim$$

$$\sim 2.6 \cdot 10^{-13} \frac{n}{T_e}$$ **~100 kV/cm**

LOW-VOLTAGE PREPULSE
~ ten kV

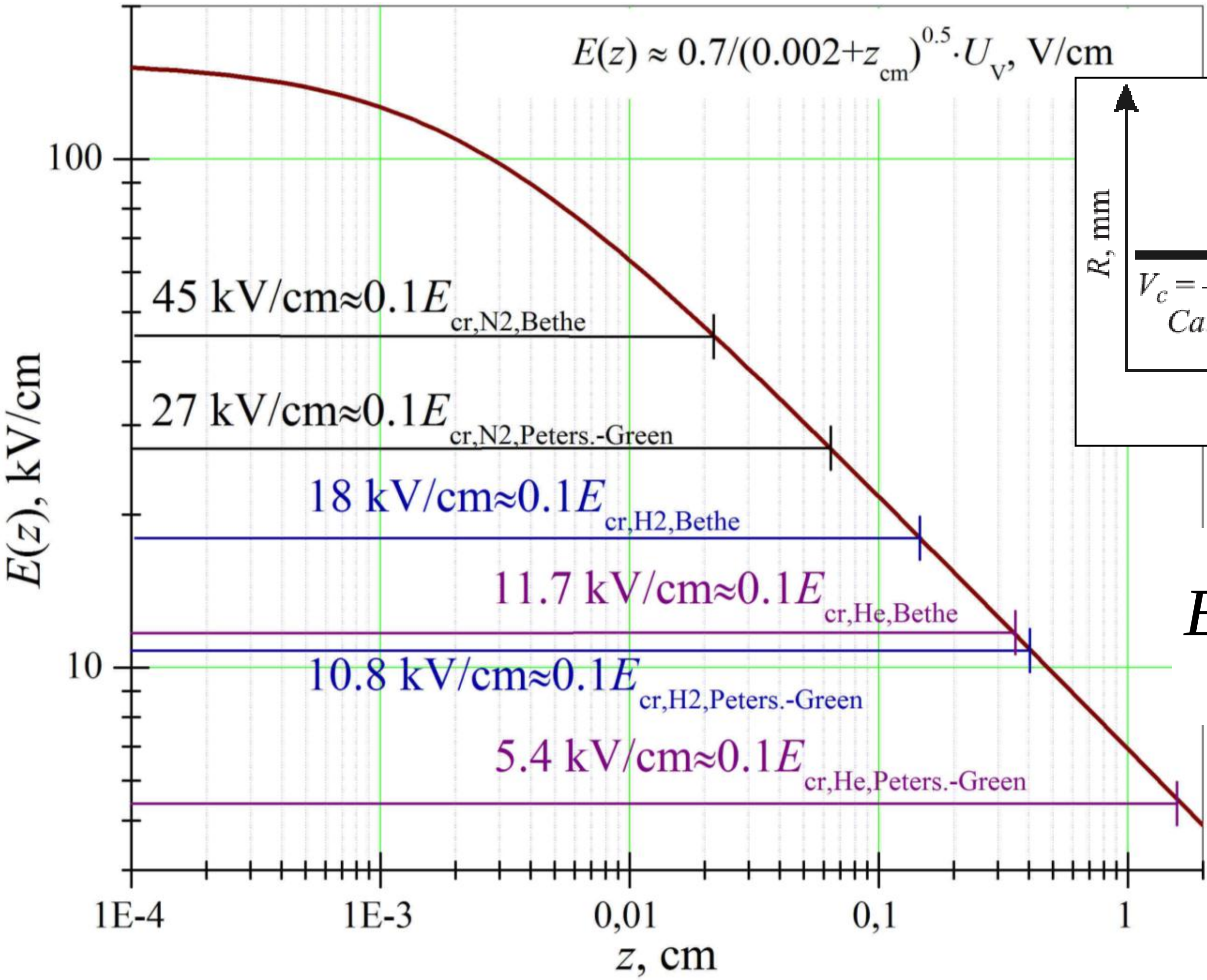
VOLTAGE WAVEFORM

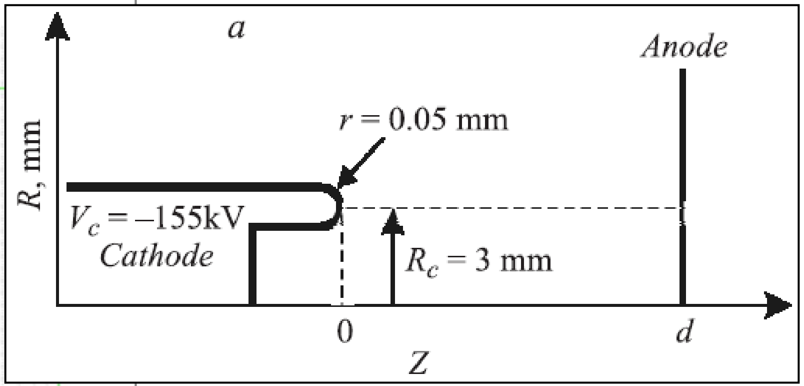
A prepulse of a low voltage, U_{pre} ~10-20 kV, and a few ns duration, t_{pre}, was applied to the diode before the main pulse



1) **The REB current I_{reb} increases with the duration t_{pre}**
2) **Field at the prepulse being likely tenfold lower than for the REB generation onset, e.g. up to 155 kV/cm**

Electric field longitudinal distribution *E*(*z*)





$$E(z) \approx \frac{0.7U_V}{\sqrt{0.002 + z_{cm}}} \frac{V}{cm}$$

The longitudinal electric field *E*(*z*) allows one to calculate the pulsed discharge parameters

CHARGED PARTICLE NUMBER GROWTH

The electric field during a nanosecond prepulse of about tens to hundreds kV/cm falls in the range typical of nanosecond pulsed gas discharges, *E*/*p* ~ 20–200 V cm^{-1} Torr^{-1}

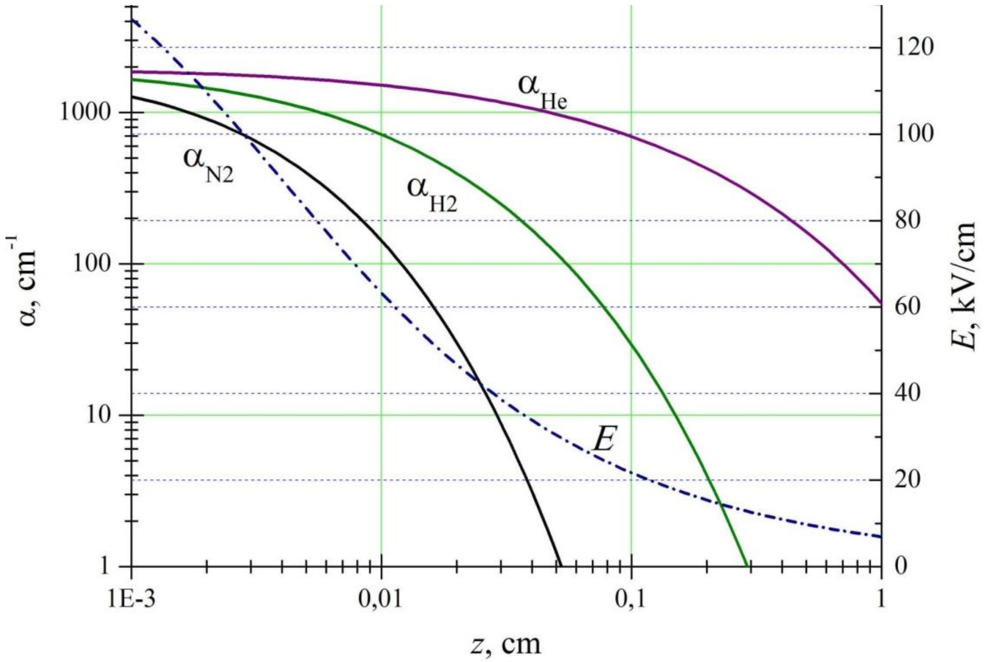
$$\frac{\partial N}{\partial z} = N \cdot \alpha(z) \qquad \frac{\partial z}{\partial t} = v_{dr.e}(z)$$

Ionization coefficient

$$\alpha = pAe^{-pB/E}$$

Electron-drift velocity

$$v_{dr.e} = C \cdot \left(\frac{E}{p}\right)^k$$



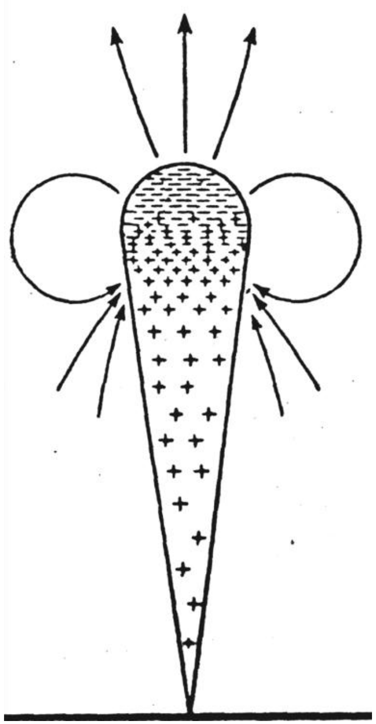
Although the field *E* isn't uniform, the drift approach for deriving α and $v_{dr.e}$ still remain valid as $\lambda_e \times |\partial \ln E/\partial z| \ll 1$

CHARGED PARTICLE NUMBER GROWTH

At the reaching of about N_{cr} ~10^8 particles the external field being perturbed by their space charge – 'streamer' appears

One can calculate the time of such a growth by the balance equation

$$\ln \frac{N(z,t)}{N_0} = \int \alpha(z) \cdot v_{dr.e}(z) dt$$



Meek J.M. 1940
Phys. Rev. **57** 722

Streamer formation time:

$$t_s = \frac{\ln N_{cr}/N_0}{\langle \alpha(z) \rangle \cdot \langle v_{dr.e}(z) \rangle}$$

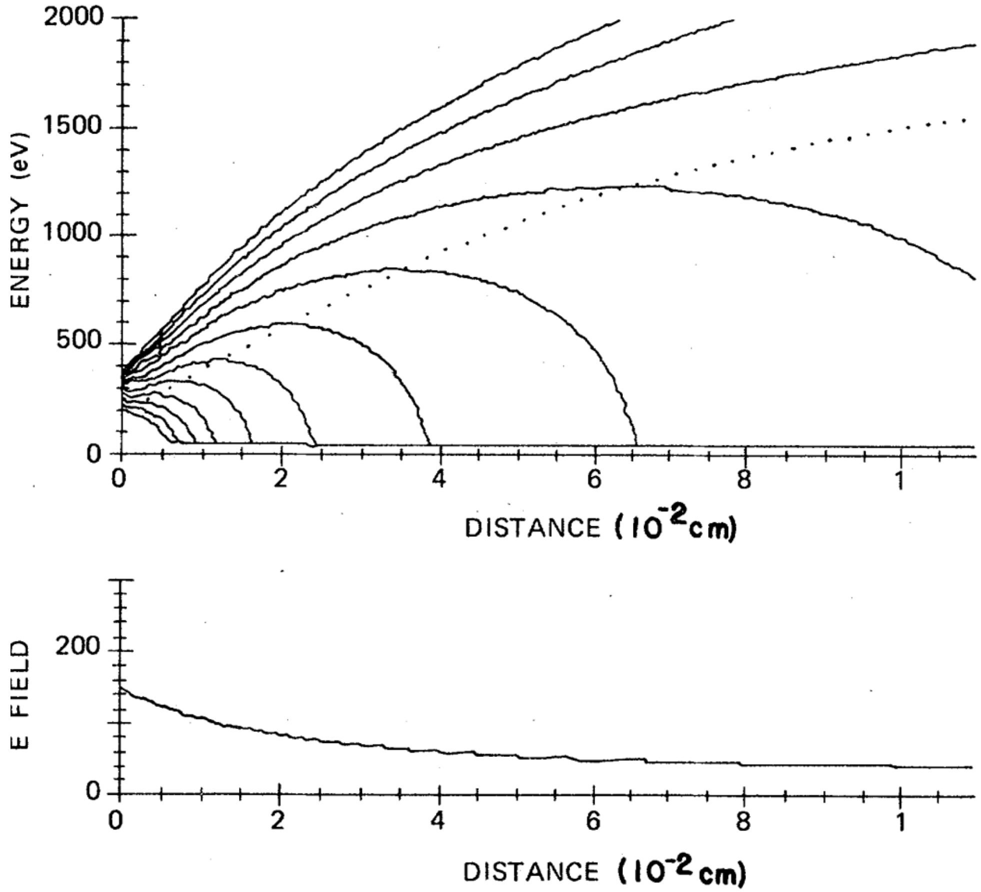
For the sake of simplicity, let us use a local values, then

$$t_s(z) \Rightarrow \frac{\ln N_{cr}/N_0}{\alpha(z) \cdot v_{dr.e}(z)} \approx \frac{20}{\alpha(z) \cdot v_{dr.e}(z)}$$

"Trapping of REs" at the PREPULSE

For the prepulse field RE acceleration mode arises, although for high-energy electrons (>100 eV)

As $E < E_{cr}$ and E strongly decreases with z, most of these REs become "trapped", i.e. their acceleration become slower than the retarding-force F_d growth [E. E. Kunhardt and W. W. Byszewski, *Phys. Rev. A* **21** 2069–2077 (1980)]

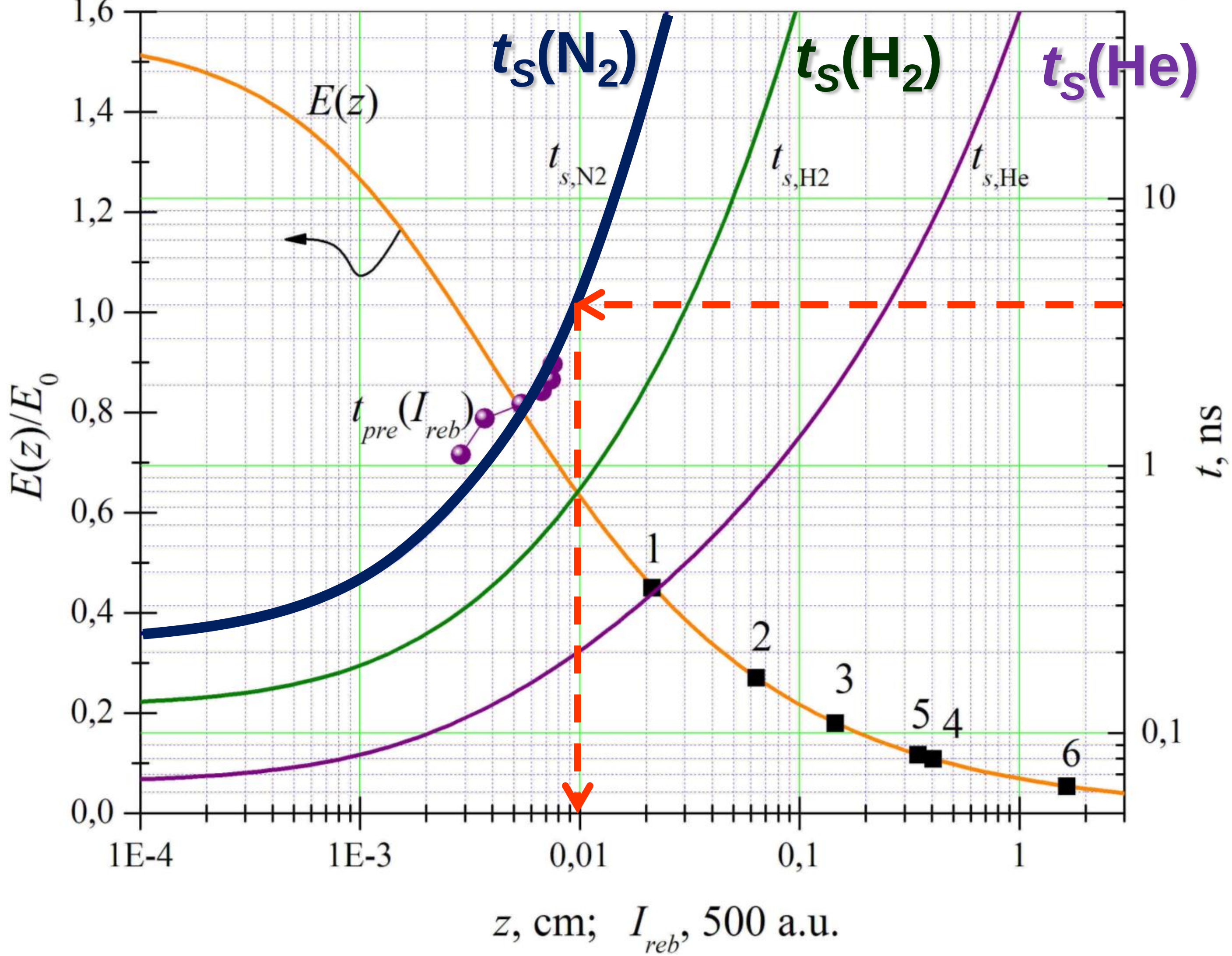


Also we neglect field distortion by space charge accumulation

Hence $$t_s(z) \approx \frac{20}{\alpha(z)\cdot v_{dr.e}(z)}$$ gives an upper estimation

PREPULSE STREAMER

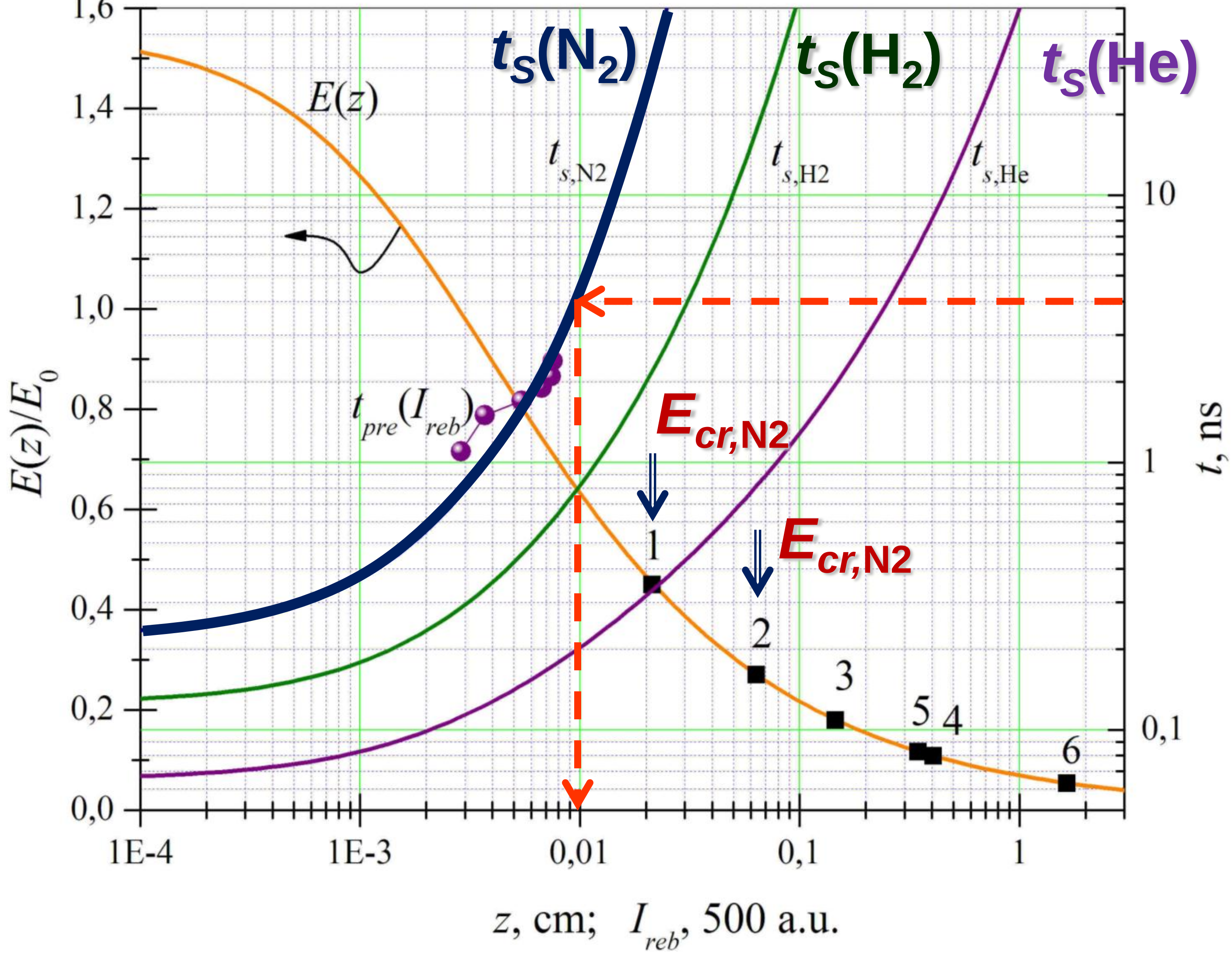
A few-ns prepulse duration is sufficient for the streamer appearance within the *z* distance of ~0.01 cm (for N_2)



$$t_s = \frac{20}{\alpha v_{dr.e}}$$

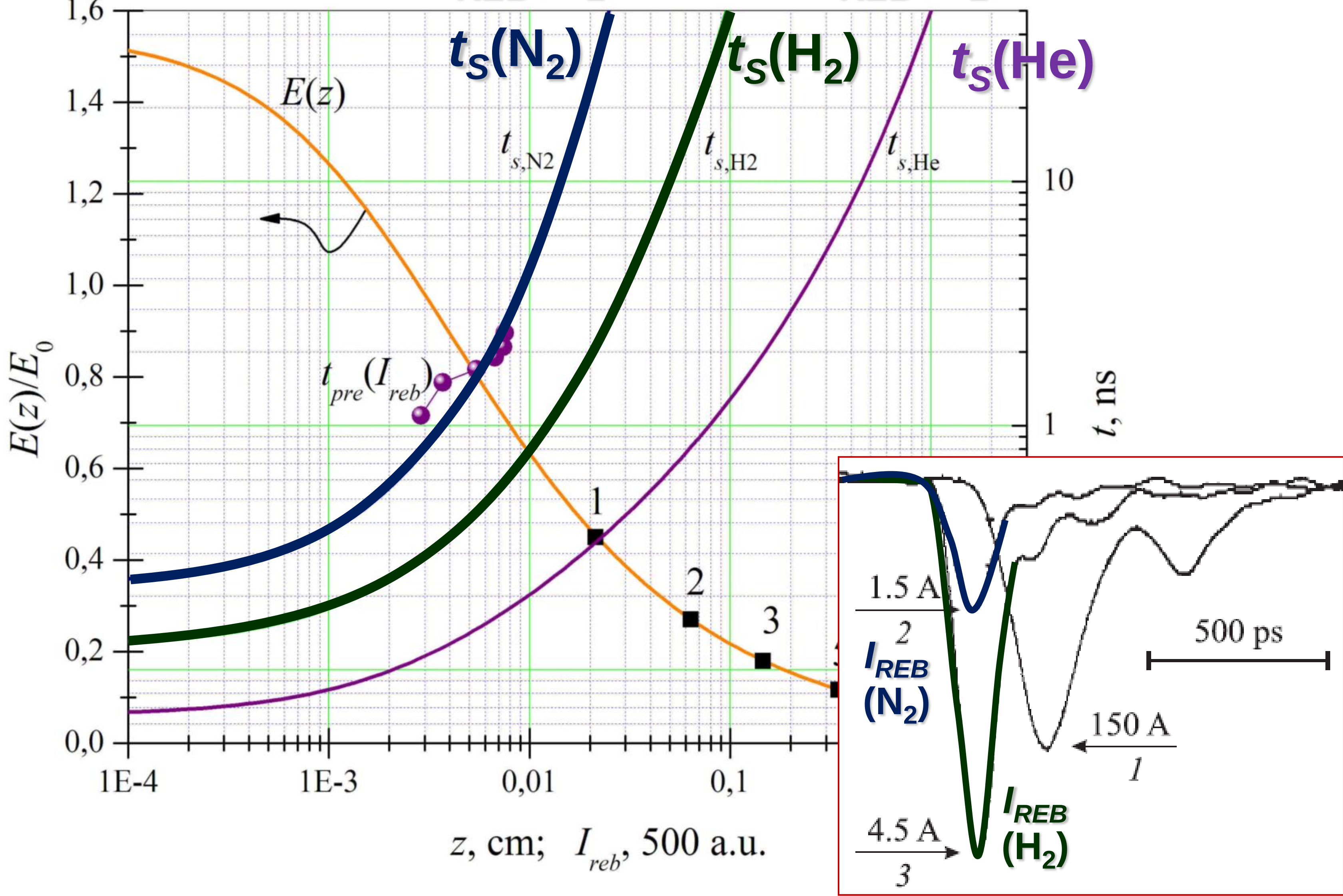
PREPULSE STREAMER

At the main pulse application streamer falls in the range of $E(z) > E_{cr}$, hence its electrons become RE ones



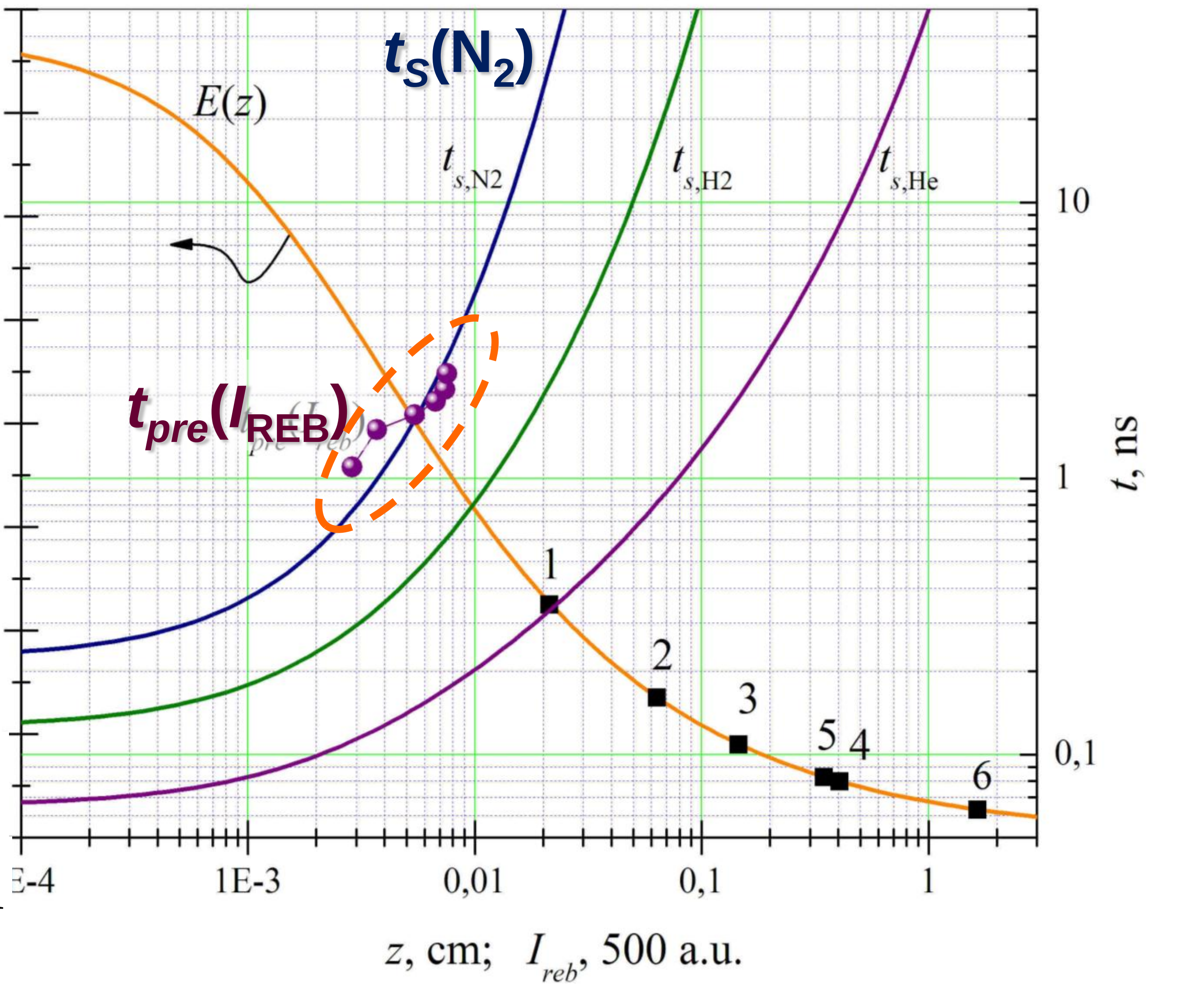
PREPULSE STREAMER

The streamer in H_2 about 3 times larger than that in N_2, as well as measured $I_{REB}(H_2)$ ≈4.5 A, $I_{REB}(N_2)$ ≈1.5 A



PREPULSE STREAMER

The experimental dependence $t_{pre}(I_{REB})$ being similar to the streamer formative time $t_s(z)$



Hence, one can predict $I_{REB}(t_{pre})$ using streamer parameters $t_s(z)$

$$I_{REB,N_2} \approx 3.5\sqrt{\frac{t_{pre}}{10\text{ns}}}\text{A}$$

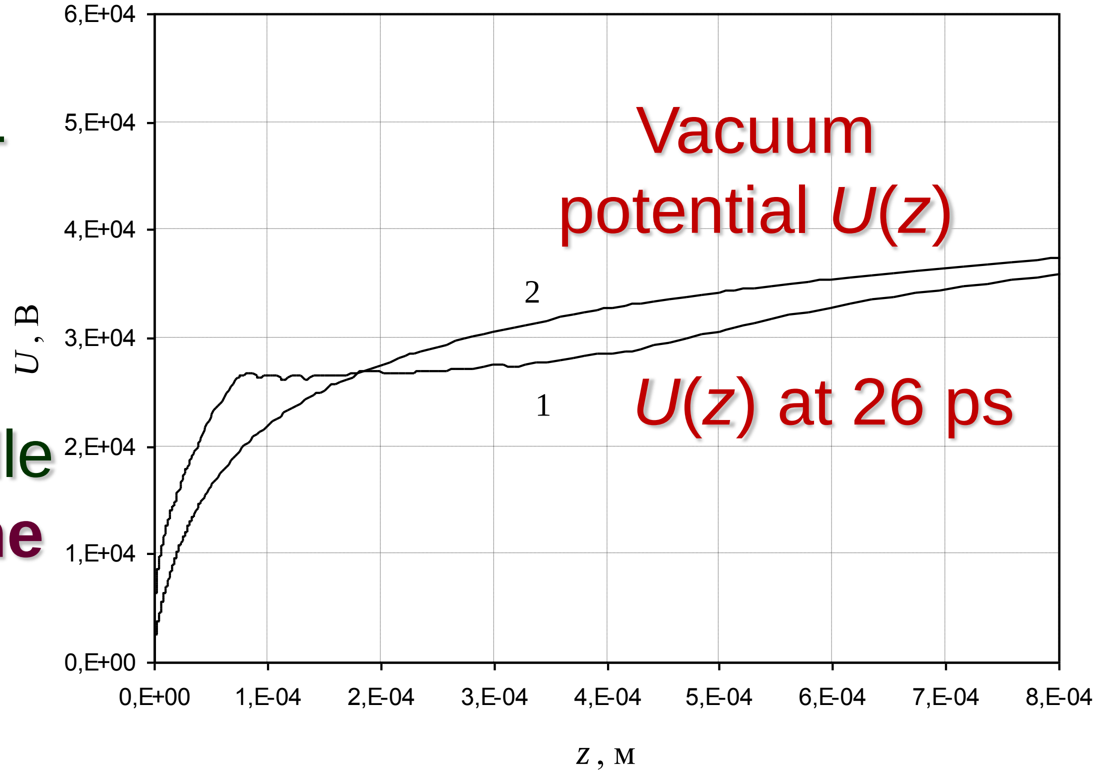
$$I_{reb,H_2} \sim 12 \cdot \left(\frac{t_{pre}}{10\text{ns}}\right)^{0.67}\text{A}$$

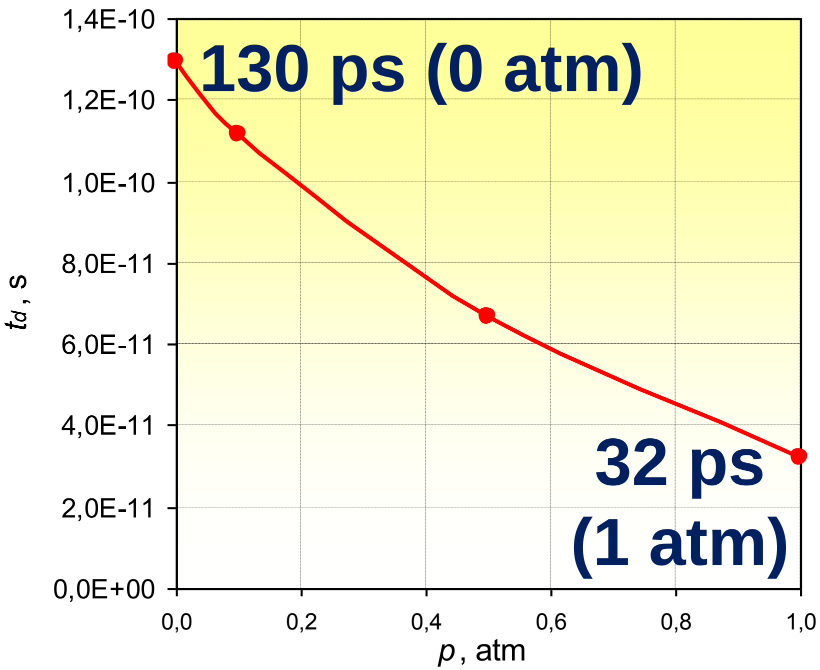
$$I_{reb,He} \sim 100 \cdot \left(\frac{t_{pre}}{10\text{ns}}\right)^{0.67}\text{A}$$

HIGH-VOLTAGE PULSE
~2 MV/ns

EMISSION, IONIZATION at *E*/*p* ~2 kV/cm/Torr

PIC-MC simulation has predicted an intense self-consistent rise of the emission current and a positive space charge buildup near cathode needle **at the main pulse risetime**





At **1 atm** of He, at **26 ps**, 54 kV, T_e in needle reaches **4300 K**, ***E* = 150 MV/cm**, j_{em} **= 7.6 GA/cm²**

1) Explosive overheating of the needle $t_d \approx 10^{2.12-0.61p,\mathrm{atm}}$ **ps**

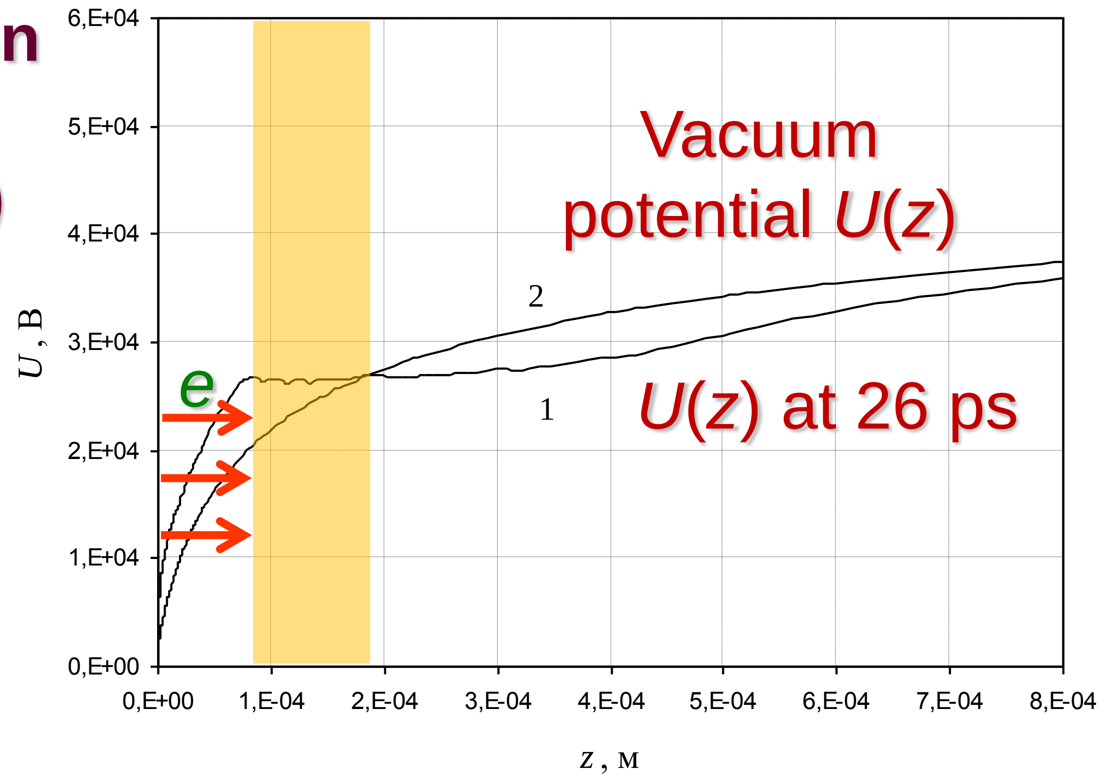
EMISSION, IONIZATION and ACCELERATION

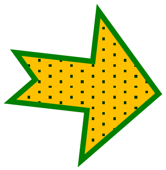
2) Electron acceleration in runaway mode in the cathode vicinity (10 μm)

$$\lambda_{Col} \sim 10^{12}\frac{T^2}{n} \sim 1\text{cm}$$

$$\tau_{Col} \sim 200\text{ps} >> t_{reb}$$

The plasma density growth (up to ~10^{20} cm^{-3}) itself does not prevent REB generation





An “anomaly” fast REB relaxation arises into the near-cathode plasma

«Langmuir paradox» (1925) – anomalous cathode beam relaxation due to the plasma Langmuir oscillations

STOPPING OF THE REB

$$\omega_{pe} = \sqrt{\frac{4\pi e^2}{m_e} n_{pl}}$$

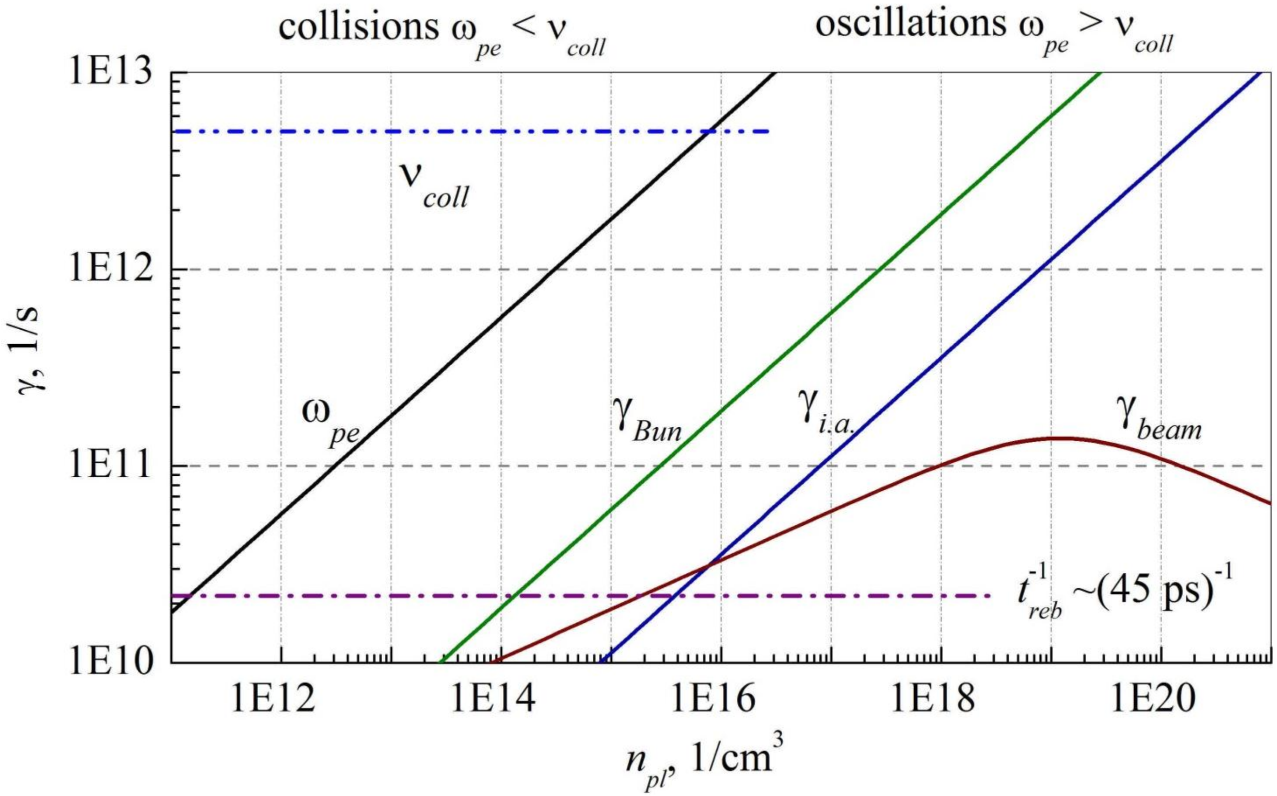
Indeed, plasma Langmuir frequency $\omega_{pe} \approx 2\cdot10^{10}$ s^{-1} $\approx 1/t_{reb}$ just at $n = 10^{11}$ **cm^{-3}**

Even the streamer density gives ~10^{13} cm^{-3} ***(at 100 V/cm/Torr)***

As the REs traverse the gap without collisions ($\nu_{coll,REB} \rightarrow 0$), this time, $1/\omega_{pe}$, can be attributed to a virtual cathode formation from REs (with their density $n_{REB} \approx n_{pl}$), similarly to that appears for vacuum diode case [S. A. Barengolts, G. A. Mesyats, and É. A. Perel'shtein, *JETP* **91** 1176 (2000)**]**

As to the cold electrons, their dynamics is governed by electron-neutral collisions with frequency $\nu_{coll,e}$ ~5×10^{12} s^{-1}, until the plasma density reaches n_{cr} ~10^{16} cm^{-3}, such that ω_{pe} becomes greater than $\nu_{coll,e}$

STOPPING OF THE REB



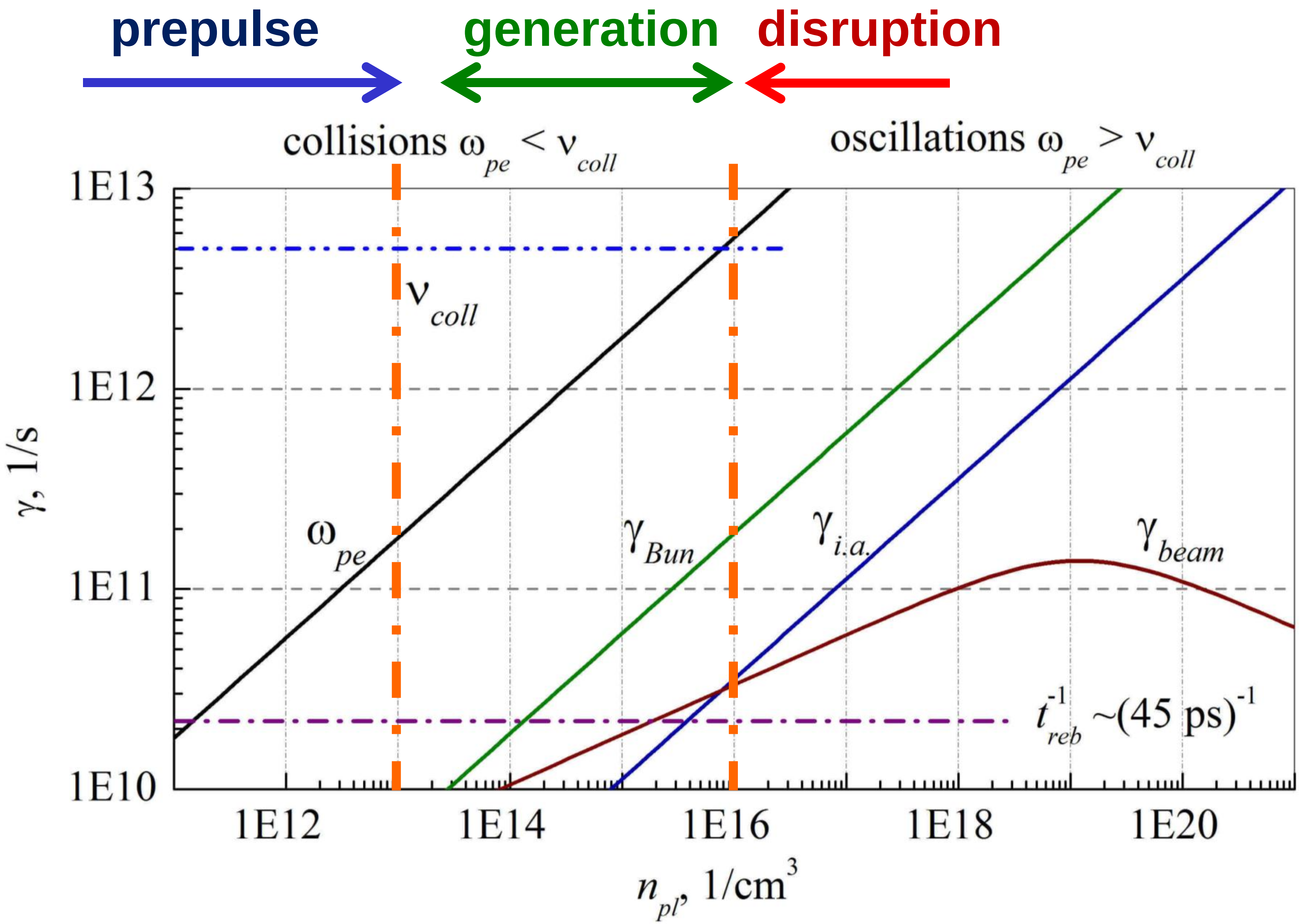
For $n_{pl} > n_{cr}$ the space charge oscillations dominate over collisions. And the increments of the electron beam instabilities (two-stream (Buneman), ion-acoustic, collisional beam ones) much larger $\mathbf{1/t_{REB}}$

$$\gamma_{Bun} \approx (m_e/M_i)^{1/3}\,\omega_{pe}$$

$$\gamma_{i.a.} \approx \omega_{pe}\sqrt{m_e/M_i}\cdot u/v_{Te}$$

$$\gamma_{beam} \approx \omega_{pe}\sqrt{\frac{n_b}{n_{pl}}\,\frac{\omega_{pe}}{2\nu_{coll}}}$$

REB GENERATION AND DISRUPTION



RÉSUMÉ

Generation and disruption of a picosecond REB at strongly overvolted gas gap has been considered from point of view of the pulsed discharge, emission-ionization dynamics, and plasma instabilities

- ✓ A streamer is initiated and grows during a few-nanosecond low-voltage (10 kV) prepulse applied to the diode gap
- ✓ Application of the main pulse (~2 MV/ns) results in generation of a REB with the streamer electrons involved in the acceleration process, in intensification of the electron emission from the cathode, and in an increase in plasma density
- ✓ The fast (~10 ps) beam instability developing in the dense plasma causes the REB to disrupt

$t_{\mathrm{REB}} = t_{n\_rise} + t_{\mathrm{instab.}}$ $\qquad$ $I_{\mathrm{REB}} = I_{\mathrm{emission}} + I_{\mathrm{streamer}} + I_{\mathrm{ioniz.}}$