On the mechanism of HPM pulse shortening in oscillators driven by relativistic electron beams

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Abstract. Microwave pulse shortening affects HPM sources even if their efficiency is sufficiently low. In such devices the electrostatic field of the REB exceeds the microwave field on the wall of the slow wave structure so that the field emission of electrons is initially impossible. In this case the reason for plasma to appear is a bombardment of the surface by relativistic electrons. They may originate with the REB, which disrupted partially in the microwave field, or the reflection from the collector. Estimations show that a bombardment of the wall surface with the energy ~ 10^{-3} J/cm^2 is sufficient for the microwave pulse shortening.

There are several reasons for the microwave pulse shortening in a relativistic oscillator, all of them depend on plasma presence, but the majority of them may be obviated completely [1, 2]. The most difficult problem is due to the plasma which appears in the slow-wave structure of a microwave oscillator. The model of the microwave pulse shortening in a BWO with high efficiency was considered in [3], there plasma generation was initiated by a multipactor in RF field on the wall. Actually, the electric field on the wall is a sum of two components, the RF field and electrostatic field of the electron beam space charge. If the RF field is comparatively small, the total electric field on the wall always hinders electrons from emission and makes the multipactor impossible. The purpose of this work was to find out if this condition, namely, comparatively low efficiency of microwave generation may prevent the effect of microwave pulse shortening.

The reason for the plasma accumulation which interrupts long-term microwave generation even with such low efficiency is the bombardment of the walls by relativistic electrons. In a general way, the scheme of the process is as follows. The walls of the slow wave structure are exposed to the bombardment by relativistic electrons which are reflected from the collector, or the REB is disrupted partially in the microwave field. The electrons strike the wall and cause a gas desorption and ionization. The REB space charge compensation allows an RF discharge (multipactor) which gives rise to plasma accumulation and culminates in the microwave pulse shortening. This scenario is especially dangerous for microwave sources with microsecond pulse duration.

Hence, the primary source of the plasma is the flux of relativistic electrons which hits the surface of the electrodynamic structure, desorbs gas and ionizes it. Plasma as a quasi-neutral media with specific properties does not appear at this stage of the process. The guiding magnetic field ~ 10 kG retains only the "newborn" electrons near the wall, in the electrostatic field $E \sim 10^5$ V/cm of the REB space charge they drift over azimuth with the speed $v_e \sim c\frac{E}{B} \sim 10^9$ cm/s. Ions rush to the axis and neither magnetic field, nor their own space charge hinders this motion. It is easy to estimate using the "3/2" law that with sufficient amount of ions near the wall and the surface density of a hollow REB ~ 10^{11}см$^{-2}$ the space charge compensation of the REB may be completed in ~ 10 ns.

The gas desorption is described by the equation:

$$n_m v_m = g_b u_b n_b \sin\alpha + g_e v_e n_e \tag{1a}$$

where n_m and v_m are the concentration and the velocity of gas molecules; g_b and g_e are the desorption coefficients of the molecules due to electrons of relativistic beam and ionized gas, correspondingly; u_b and n_b are the velocity and the concentration of relativistic electrons; α is an angle between the velocity of relativistic electrons and the surface; n_e is the concentration of electrons drifting near the wall. The first item in the sum describes the gas desorption by relativistic electrons and the second one is due to the drifting "slow" electrons.

The ionization of the desorbed gas develops in accordance with:

$$\frac{dn_e}{dt} = n_m\left(\sigma_b u_b n_b + \sigma_e v_e n_e\right) \tag{1b}$$

where σ_b и σ_e are the cross sections of gas ionization by relativistic and drifting electrons, correspondingly. The same way as above, the first item in the brackets describes the gas ionization by relativistic electrons and the second one is due to the "slow" electrons.

The formulas (1a) and (1b) may be presented together as:

$$\frac{dn_e}{dt} = \frac{g_e v_e}{v_m}\left[\frac{g_b u_b \sin\alpha}{g_e v_e} n_b + n_e\right]\cdot \sigma_e v_e \left[\frac{\sigma_b u_b}{\sigma_e v_e} n_b + n_e\right] \tag{2}$$

For estimations we may admit that the velocities are: $u_b \approx c$ and $v_m \sim 10^5$ cm/s. The ionization cross sections are $\sigma_b \approx 3\cdot 10^{-18}$ cm^2, and $\sigma_e \approx 3\cdot 10^{-16}$ cm^2. The desorption coefficient rises from $g_e \sim 10^{-3}$ for the energy of electrons ~ 100 eV [4] to $g_b \sim 10$ for 70 keV [5]. The minimal estimation of the angle α corresponds to the length of the slow-wave structure of ~ 1 m and the gap between the REB and the wall ~ 1 cm, i. e. $\alpha \sim 0.01$. More probably, the value of α corresponds to pitch-angles of relativistic electron trajectories; for the electrons originated from the REB $\alpha \sim 0.1$. Taking into account that the desorption coefficient g_b rises with decreasing α and with an increase in energy of electrons, the value of the product $g_b\cdot\sin\alpha \sim 10$ seems not to be an overestimation.

With the above estimations, the formula (2) results in:

$$\frac{dn_e}{dt} \sim 3\cdot 10^{-6}\cdot\left[3\cdot 10^5\cdot n_b + n_e\right]\cdot\left[0.3\cdot n_b + n_e\right] \tag{3}$$

Electrons nascent at the distance from the surface less than:

$h = 2\frac{v_e}{\Omega} = 2c\frac{E}{B}\cdot\frac{mc}{eB} = 2\frac{mc^2}{e}\frac{E}{B^2}$ ~ 10^{-2} cm, settle on the wall, see Fig. 1. This takes place until the moment t_0 when the gas expands and the ionization begins at the distance $h \sim v_m t_0$ from the wall:

$$t_0 = 2\frac{v_e}{\Omega}\frac{1}{v_m} = 2\frac{mc^2}{ev_m}\frac{E}{B^2} \tag{4}$$

Hence, in about $t_0 \sim 10^{-7}$ s after the start of the bombardment the azimuthal drift of electrons in the crossed E and B fields may start. Moving so, the electrons gain energy ~ 0.1 — 1 keV.

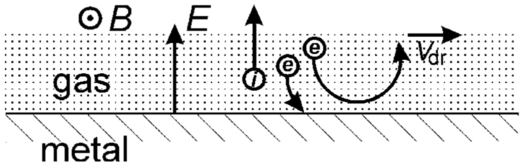

Fig. 1. Movement of ions *i* and electrons *e* in the field of the REB space charge and guiding magnetic field.

For the processes describing by the equation $\frac{dn}{dt} = A[B+n][C+n]$ where $B >> C$, the character time intervals at every stage are equal to $t_1 \sim (AB)^{-1}$, the total duration is $t_{total} \sim \left(2 + \ln\frac{B}{C}\right)\frac{1}{AB}$. The compensation of the REB by ions accordingly to f.(2) and an accumulation of electrons near the wall perform with a character time:

$$t_1 \sim \frac{v_m}{\sigma_e v_e \cdot u_b g_b \sin\alpha}\cdot\frac{1}{n_b} \tag{5}$$

and continues $\ln\left(\frac{g_b \sin\alpha}{g_e}\frac{\sigma_e}{\sigma_b}\right) + 2$ ~ 10 times longer. Taking into account the above estimations and f.(5) it is easy to obtain: $n_b \cdot t_1 \sim 1$[s/cm^3]. During the character time t_1 the surface is exposed to the bombardment by relativistic electrons with the energy $W \sim mc^2 \cdot n_b \cdot t_1 c \cdot \sin\alpha = mc^3 \cdot (n_b t_1) \cdot \sin\alpha \sim 10^{-4}$ J/cm^2 for $\alpha \sim 0.1$. The total duration of the process is $\sim 10 \cdot t_1$, so the total energy of bombardment is $\sim 10^{-3}$ J/cm^2, e. g., 10^{-7}[s]$\cdot 10^{6}$[V]$\cdot 10^{-2}$[A/cm^2].

By the complete compensation of the REB space charge near the wall there are electrons with the surface density ~ 10^{11} cm^{-2} (equal to that of the REB) and a gas layer with the surface density at least $\rho_m = n_b \cdot t_{total} u_b \cdot g_b \sin\alpha \sim 10^{12}$ cm^{-2}. In RF field only available electrons can ionize this gas completely during $(n_m \cdot \sigma_e \cdot v_e)^{-1}$ = $t_{total} \cdot (\rho_m \cdot \sigma_e \cdot v_e / v_m)^{-1} < t_{total}$ even without the mechanism [3], i. e. without electron emission from the wall and the multipactor. Actually, the process will go faster. As a result, a layer of plasma appears on the wall with the surface density ~ 10^{12} cm^{-2}.

The microwave pulse shortening is due to the plasma which distorts the dispersion properties of the waveguide and may change the REB parameters. If REB excites the lower E-mode of hollow plasma then the threshold is [6]:

$$\omega_p^2 = k_\perp^2 u_b^2 \gamma^2 = \frac{\left(\gamma^2 - 1\right)c^2}{\Delta \cdot r_p \cdot \ln \dfrac{R}{r_p}}, \qquad (6)$$

where γ is a relativistic factor, R is the waveguide radius, r_p and Δ are the plasma radius and thickness. Therefore, the surface density of plasma is:

$$n_p \cdot \Delta = \frac{\left(\gamma^2 - 1\right)mc^2}{4\pi e^2} \frac{1}{r_p \cdot \ln \dfrac{R}{r_p}}. \qquad (7)$$

For $\gamma = 2$ and $r_p = 2$ cm this value $n_p \cdot \Delta \sim 10^{12}$ cm^{-2} is the same as the above indicated surface density of plasma which is accumulated near the wall. The layer of plasma with the surface density $\sim 10^{12}$ cm^{-2} in RF field will cause the further accumulation and expansion of plasma, excitation of "parasitic" modes and dispersion of electrons of the REB. In these circumstances, the microwave pulse duration of a vacuum microwave source will be limited.

Hence, the compensation of the REB space charge and the following microwave pulse shortening may be caused by a minor, $\sim 10^{-3}$ J/cm^2 $\propto$ 10^{-2} A/cm^2 bombardment of the wall by relativistic electrons. This bombardment may be provided by relativistic electrons reflected from the collector in the case of traditional axially symmetric collector [7]. If the reflected electrons are eliminated completely [1] then the bombardment may not precede but accompany microwaves in the device. The movement of relativistic electrons to the wall due to the radial $[E_z \times B_\varphi]$ drift in microwave field [8] is proportional to the radiation power. Estimations [9] show that in the field $E_z \sim 10^5$ V/cm relativistic electrons shift several millimeters toward the wall. The mechanism of the REB charge compensation and microwave pulse shortening does not differ from that described above.

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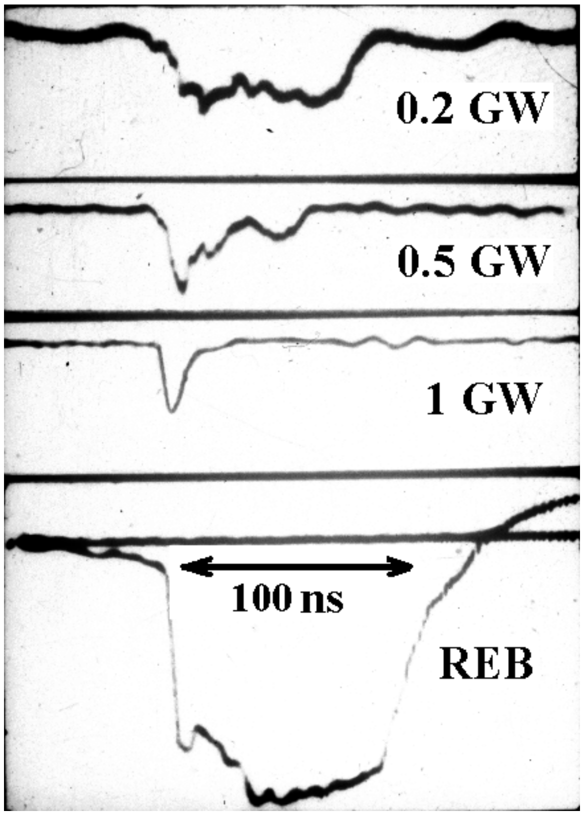
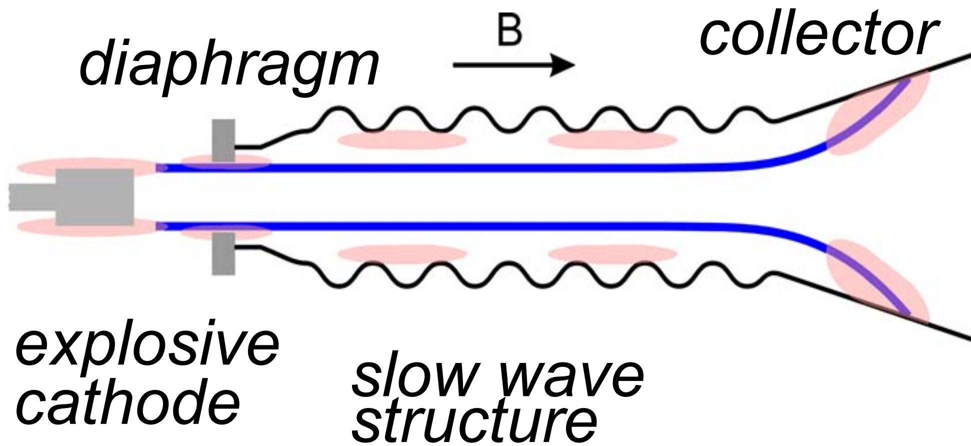
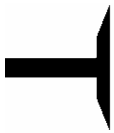
The effect of microwave pulse shortening





Yu.F.Bondar, et al., *Plasma Phys. Rpts.*, 1983, **9**(2)

Reasons for microwave pulse shortening



O.T.Loza, P.S.Strelkov
BEAMS'98

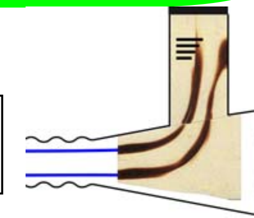
explosive cathode

diaphragm

slow wave structure

S.N.Voronkov, O.T.Loza, P.S.Strelkov
BEAMS'90

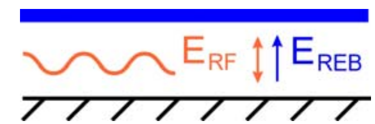
collector



low pressure: $<10^{-4}$ Tor

residual gas

wall



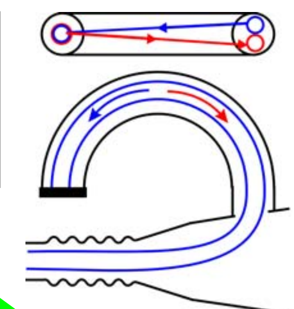
electron impact

RF

low efficiency: $E_{REB} > E_{RF}$

electrons from REB

electrons reflected from the collector



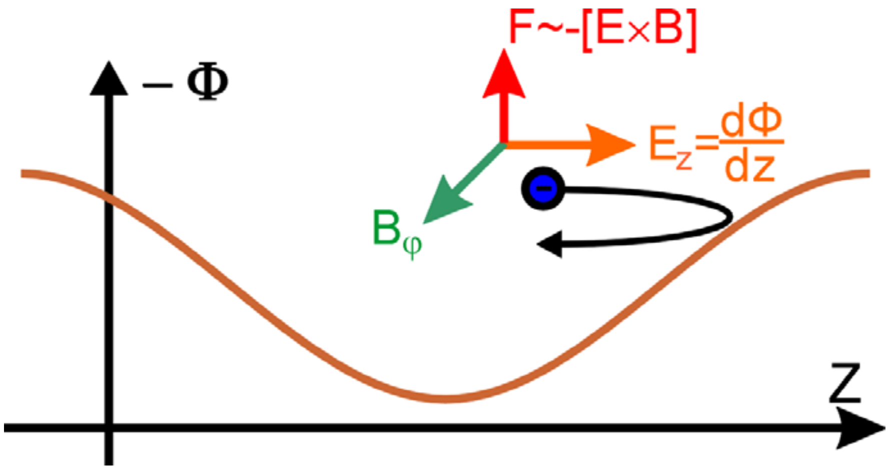
O.T.Loza, et al.
IEEE Trans. on Plasma Sci.,1998, **26**(3)

REB destruction in RF field: *model*

mechanism

(Cherenkov devices)

$$u_b \approx \frac{\omega}{k_z}$$



A. F. Aleksandrov et al. *Sov. Tech. Phys. Lett.* , 1988, **14(**9)

shift

to the wall

$$\langle \Delta r \rangle \approx 3.3\,mm \cdot \underbrace{\frac{L}{30\,cm} \cdot \left[\frac{E \big/ 100\,\frac{kV}{cm}}{B_0 \big/ 1T} \right]^2}_{\sim 1} \propto \boldsymbol{P}$$

J. Benford, and G. Benford, *IEEE Trans. on Plasma Sci.* 1997, **25**(2)

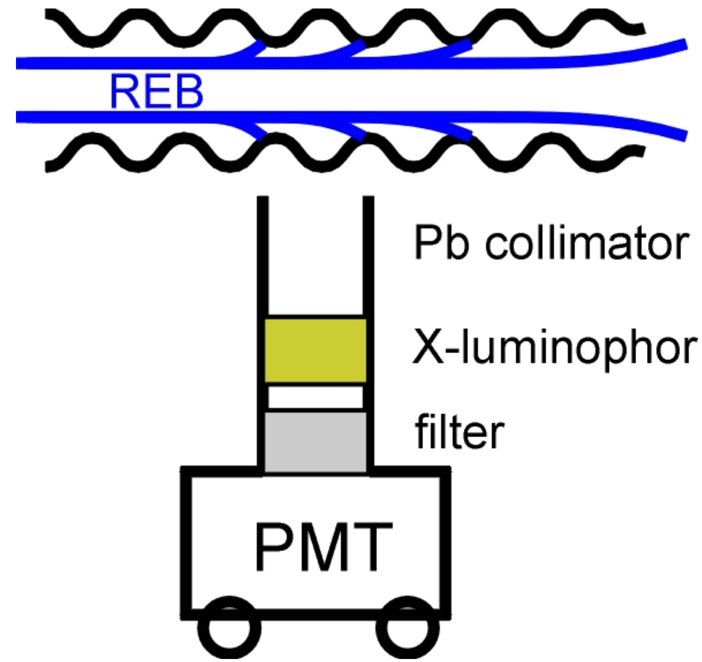
REEB destruction in RF field: *experiments*

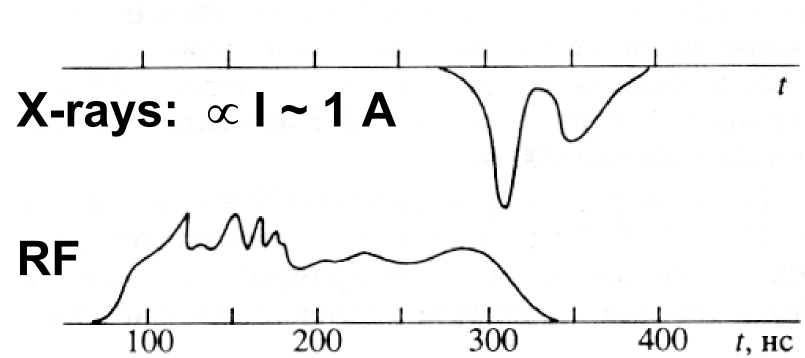
RF 10^{10} W

deposition of REB on the wall:

1 кA ∝ 10% of the total current

S.P.Bugaev et al. *J. Communic. Techn. and Electronics*, 1984, **29**(3).





O.T.Loza, et al. *Plasma Phys. Rpts.*, 1994, **20**(4)

Gas desorption and ionization

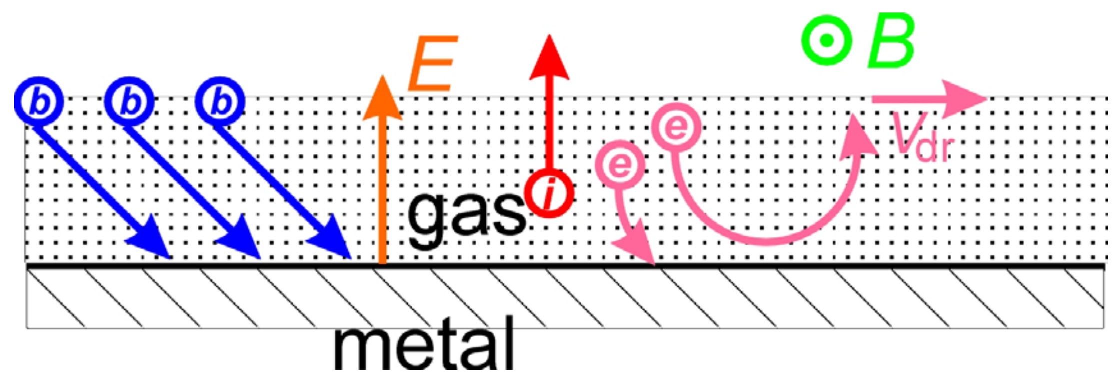
desorption of gas
by electrons of REB,
ionization of gas
by electrons of REB

$n_p \sim 3\cdot10^{-1}\, n_b$

desorption of gas
by electrons of REB,
ionization of gas
by drifting electrons

$n_p \sim 3\cdot10^{5}\, n_b$

desorption of gas
by drifting electrons,
ionization of gas
by drifting electrons



$$\frac{dn_p}{dt} = \overbrace{\frac{g_e v_e}{v_m}\left[\underbrace{\frac{g_b u_b \sin\alpha}{g_e v_e}}_{\sim 3\cdot10^{5}} n_b + n_p\right]}^{\text{desorption}} \cdot \overbrace{\sigma_e v_e \left[\underbrace{\frac{\sigma_b u_b}{\sigma_e v_e}}_{\sim 3\cdot10^{-1}} n_b + n_p\right]}^{\text{ionization}}$$

A little bit of mathematics…

$$\frac{dn}{dt} = A[B+n][C+n], \quad B >> C$$

1. n < C, $dn/dt \sim ABC$, $n \sim C$ after $t \sim (AB)^{-1}$
2. B > n > C, $dn/dt \sim ABn$, $n \propto \exp(t/\tau)$, $\tau = (AB)^{-1}$
3. n > B, $dn/dt \sim An^2$, $n \propto -1/A \cdot 1/(t-\tau)$, $\tau = (AB)^{-1}$

total time: $\sim \left(1 + \ln\frac{B}{C} + 1\right) \cdot (AB)^{-1}$

Threshold of microwave pulse shortening

character time:

$$\tau \sim \underbrace{\frac{\nu_m}{\sigma_e v_e \cdot u_b g_b \sin\alpha}}_{\sim 1\ \mathrm{s/cm^3}} \cdot \frac{1}{n_b}$$

total time:

$$t \sim \underbrace{\ln\left[\frac{g_b u_b \sin\alpha}{g_e v_e} \cdot \frac{\sigma_e v_e}{\sigma_b u_b}\right]}_{\sim 10} \cdot \tau$$

energy of bombardment
by electrons of REB

$$W \sim mc^2 \cdot n_b c \cdot \sin\alpha \cdot t = mc^3 \cdot (n_b t) \cdot \sin\alpha$$

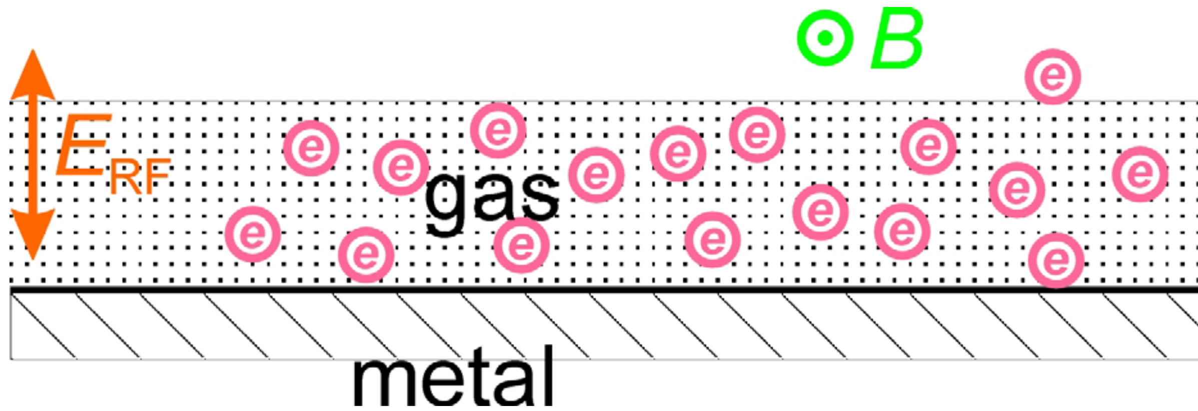
pitch-angles:
$\sin\alpha \sim 0.1$

$W \sim 10^{-3}$ J/cm^2

e.g., 0.01 A/cm^2·1 MV·100 ns
or 10 A on $\underbrace{(15\ \mathrm{cm})}_{L} \cdot 2\pi \cdot \underbrace{(10\ \mathrm{cm})}_{R} \sim 10^3\ \mathrm{cm}^2$

Accumulation of plasma in RF field

after the compensation of REB space charge



gas: $n_b tc \cdot g_b \sin\alpha \sim 10^{12}$ cm^{-2}

+

electrons: $\sigma \approx \sigma_{REB} \sim 10^{11}$ cm^{-2}

+

RF: $E \sim 10^5$ V/cm

plasma:

$\mathbf{n_p \Delta \sim 10^{12}}$ **cm^{-2}**

Microwave pulse shortening: mechanism

Excitation threshold
of the lower E-mode
in hollow plasma
by REB

$$\omega_p^2 = (\gamma^2 - 1) k_{tr}^2 c^2$$

$$k_{tr}^2 = \left(\Delta \cdot r_p \cdot \ln \frac{R}{r_p} \right)^{-1}$$

$$n_p \cdot \Delta = \frac{(\gamma^2 - 1) mc^2}{4\pi e^2} \frac{1}{r_p \cdot \ln \frac{R}{r_p}}$$

$n_p \Delta \sim 10^{12}$ cm^{-2}

M. V. Kuzelev et al. *Plasma Phys. Rpts.*, 1983, **9**(6)

Microwave pulse shortening:

destruction of REB *in RF field*

↓

bombardment *of the wall by electrons of REB*

↓

gas ***desorption*** *and ionization*

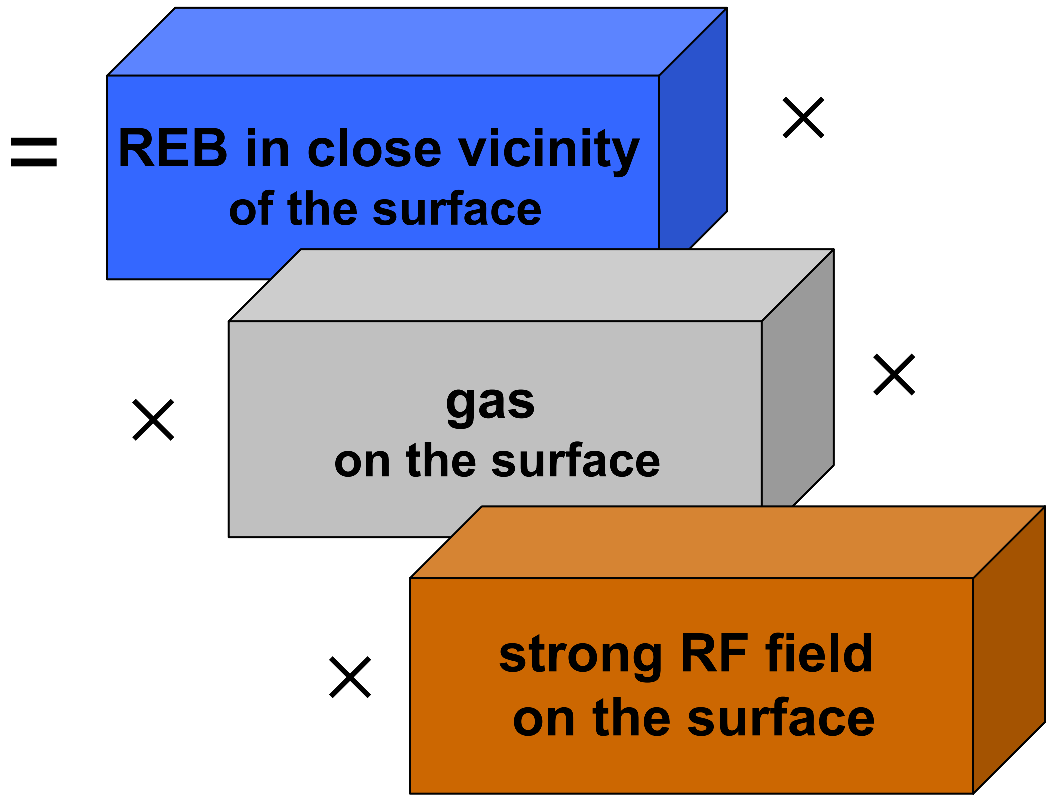
↓

accumulation *of plasma in a strong RF field near the wall*

↓

microwave pulse shortening

Intensity =



Strong RF field on the surface

H_{0n} modes

$\boldsymbol{E}$ = 0 on the wall

☺ **RF: 6 μs** × ***7*** MW , η = 45%

☹ **mode competition:**

$H_{21} > H_{01}$ at U > 250 кВ

N. I. Zaitsev et al. *Sov. Tech. Phys. Lett.*, 2001, **27**(7)

multiwave microwave oscillators *with spatially developed electrodynamic structure*

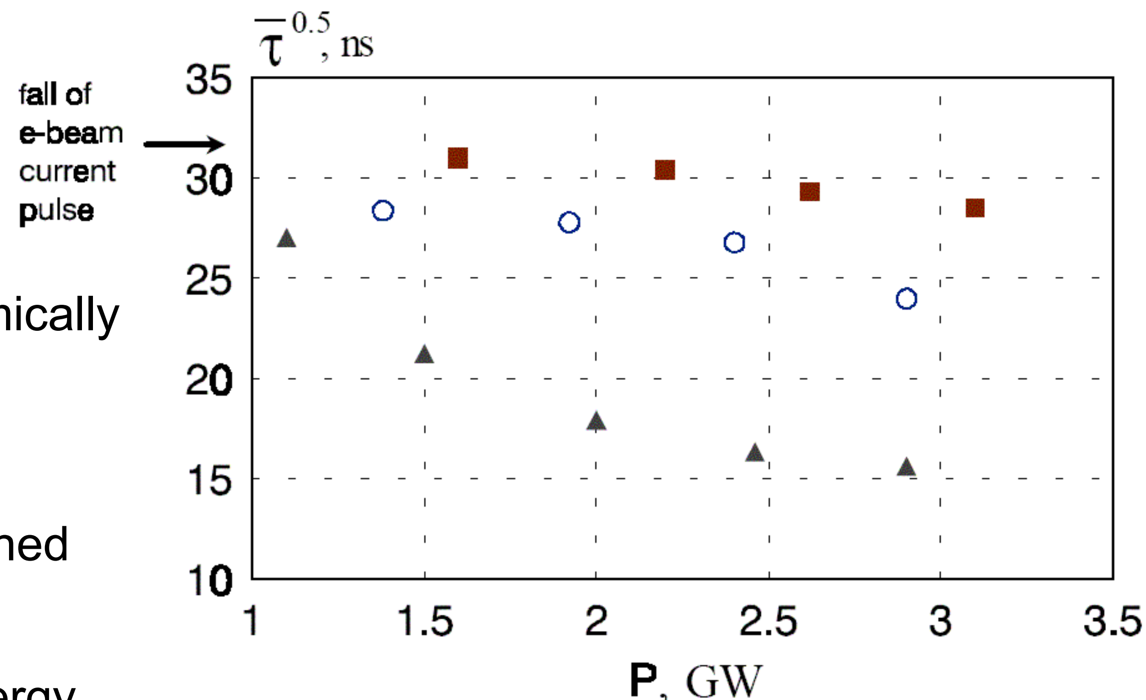
☺ **RF: 100 ns** × 5 GW = 500 J

☹ **REB: 1000 ns**

☹ **mode competition**

S. P. Bugaev et al. *Doklady Physics*, Tech. Phys., 1988, **298**(1)

Gas on the surface



▲ oil vacuum, electrochemically polished SWS

○ oil-free vacuum, electrochemically polished SWS

■ oil-free vacuum, low-energy high-current electron beam-treated SWS, 10 — 20 J/cm^2

A. M. Gaponenko, et al. Proc. BEAMs'2000, p.730

REB in close vicinity of the surface

$E_{REB} \sim 10^5$ V/cm

$\Delta \sim 1$ cm

$\Phi_b \sim 100$ kV