INVESTIGATION OF LOW-PRESSURE ICRF DISCHARGE IN A SELF CONSISTENT FORMULATION

Shemakhin A.Yu. [1] , Zheltukhin V.S. [1,2] , Samsonova E.S. [1,2] and Terentev T.N. [1,@]

1. Kazan Federal University, Kremlyovskaya Street 18, Kazan, Tatarstan 420008, Russia

2. Kazan National Research Technological University, Karl Marx Street 68, Kazan, Republic of Tatarstan 420015, Russia

@: terentievt@yandex.ru

Introduction

An effective method for modifying the surfaces of materials of various physical nature is plasma processing of radio-frequency (RF) discharges at low pressure (13.3-133 Pa) [1], one of the varieties of which is an induction discharge.

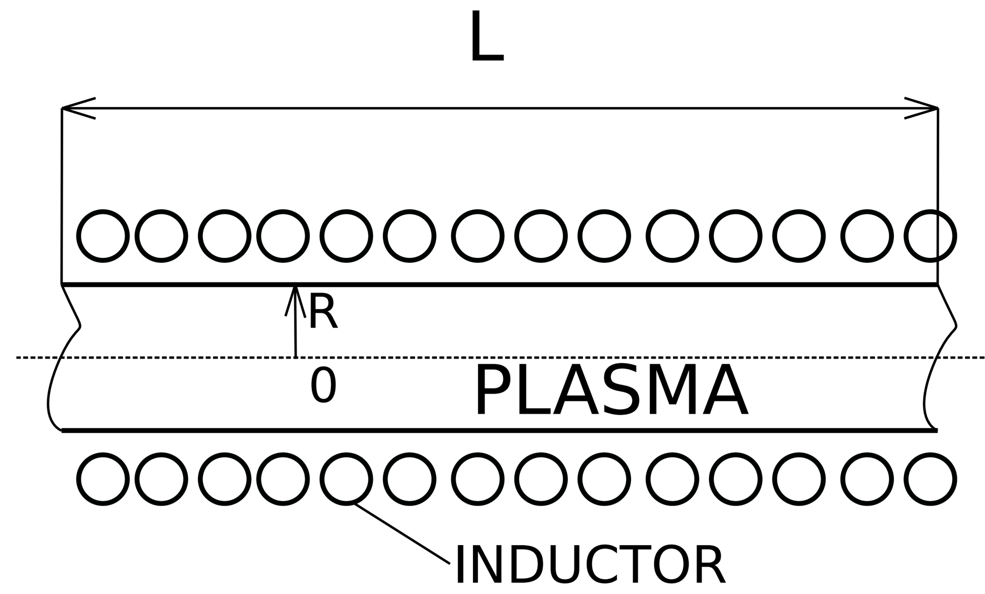


fig. 1. The 1D model of infinite plasma torch

System of equations as a self-consistent eigenvalue problem

The operating parameters of the ICRF plasma torch can be obtained using mathematical modeling methods. For this, a 1D mathematical model of the ICRF discharge is considered, which includes the transformed Maxwell equations, the stationary form of the electron balance equation, and the energy conservation equation (1). With boundary conditions (2).

$$\begin{cases} \frac{1}{r}\frac{d}{dr}\left(\frac{r}{\sigma}\frac{dH^2}{dr}\right)=2\sigma E^2 \\ \frac{1}{r}\frac{d}{dr}\left(\frac{1}{r}\frac{d}{dr}(r^2E^2)\right)=2\mu_0\omega H^2 \\ \frac{d}{dr}\left(rD_A\frac{dn_e}{dr}\right)+\nu_i n_e=0, \end{cases} \quad (1)$$

$$\begin{cases} \left.\frac{dH^2}{dr}\right|_{r=0}=0,\ \left.H^2\right|_{r=R}=H_R^2; \\ \left.E\right|_{r=0}=0,\ \frac{1}{r^2}\frac{d}{dr}(r^2E^2)|_{r=R}=0; \\ \left.\frac{dn_e}{dr}\right|_{r=0}=0,\ \left.\frac{dn_e}{dr}\right|_{r=R}=\frac{\gamma}{D_e}\cdot n_e; \end{cases} \quad (2)$$

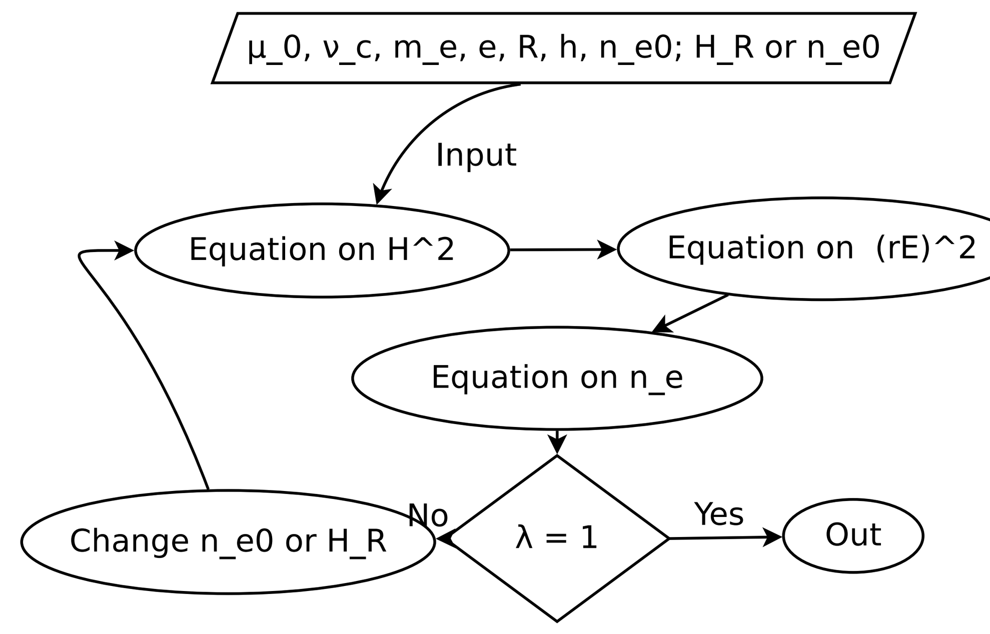


fig. 2. An iterative method diagram

Here E is the modulus of the electric field, H is the modulus of the magnetic field, σ is the conductivity, D_A is the ambipolar diffusion coefficient, n_e is the concentration of electrons, ν i is the ionization frequency, k_B is Boltzmann's constant.

We note that n_e=const is the solution for the electron diffusion equation. However the solution should be nontrivial, This fact means that the problem is an eigenproblem. The electron diffusion equation can be rewrite in the dimensionless form:

$$-\frac{1}{\rho}\frac{d}{d\rho}\left(\rho\overline{D}\frac{d\overline{n}}{d\rho}\right)=\frac{R^2\nu_{i0}}{D_{a0}}\overline{\nu n}=\lambda\overline{\nu n} \quad (3)$$

where ρ = r/R, D = D_a /max (D_a) , n = n_e /max (n_e) , ν = ν_i /max (ν_i) , α=α/max (D_a), λ = max $(\nu_i)R^2/\max(D_a)$. As far as n ≥ 0 ⇒ λ ≡ λ_0 = min λ_k , k=0,1,2,...

It is known that the minimum eigenvalue is the infimum of the Rayleigh quotienton the set of all possible functions that are not identically equal to 0, and is attained on the eigenfunction corresponding to the least eigenvalue.

$$\lambda_0=\frac{\int_0^R D_a(\frac{E}{p})(\frac{dn_e}{dr})^2 r dr}{\int_0^R \nu_i(\frac{E}{p})n_e^2 r dr} \quad (4)$$

Go back to the primary equation on n_e we obtain that the problem has the nonnegative nontrivial solution if and only if the condition λ_0=1.

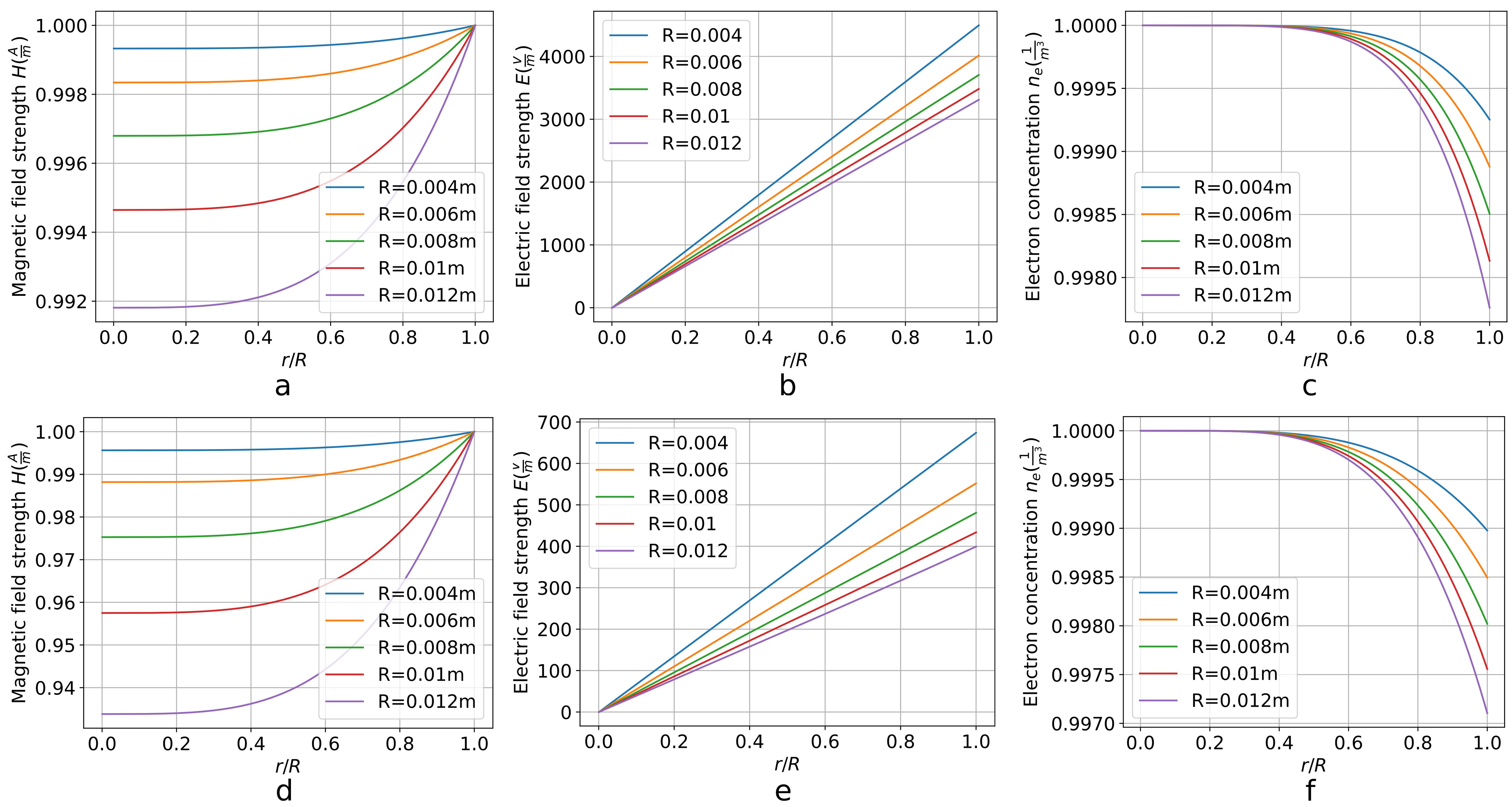
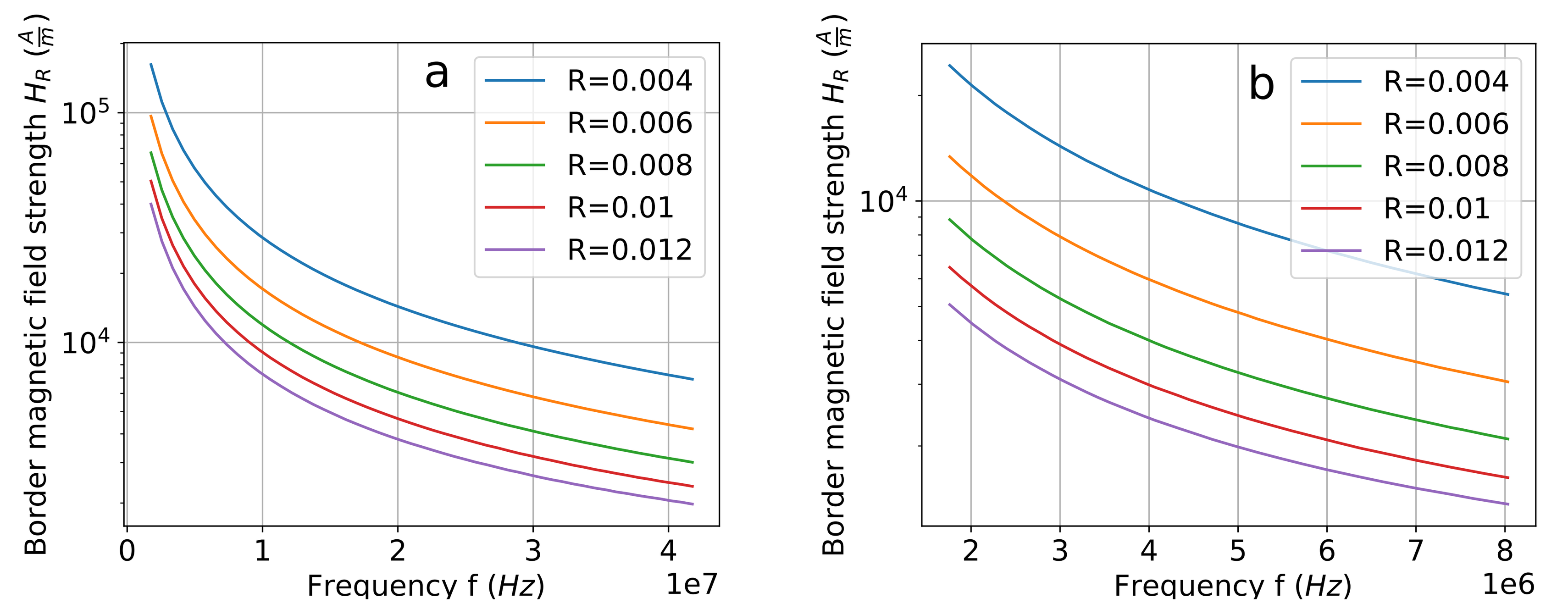


fig. 3. Dependences of the magnetic field strength (a)(d), electric field strength (b)(e), electron concentration (c)(f) along the plasma torch with radius R. (a), (b), (c): p=1000 Pa, f=1.76 MHz. (d), (e), (f): p=133 Pa, f=1.76 MHz.



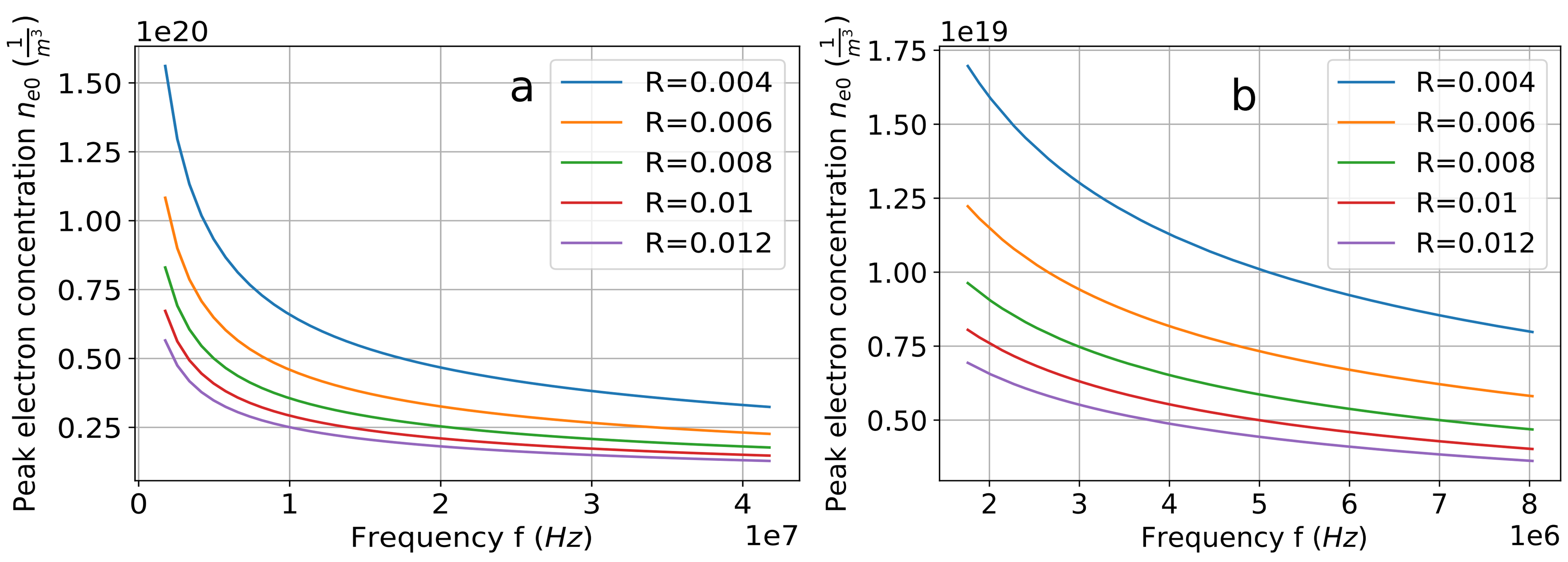


fig. 4. Distribution of H_R and n_{e0} on frequency. (a): 1000 Pa, (b): 133 Pa

Acknowledgements: Work was supported by Russian Science Foundation, project No. 19-71-10055.

References:

1. Dresvin, S. V. Donskoi, A. V. , Goldfarb, V. M., and Klubnikin, V. S. Physics and technology of low-temperature plasmas. Iowa State University Press (1977)

2. Abdullin I.Sh., Zheltukhin V.S., Kashapov N.F.: Radio-Frequency Plasma Treatment of Materials at Low Pressures. Theory and Practice of Application. Kazan Publishing House University, Kazan