IAP RAS

Submillimeter planar gyrotrons with transverse extraction of electromagnetic energy

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Submillimeter gyrotrons

Operating frequency ~1 THz

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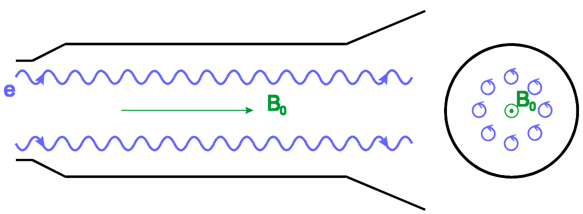
Conventional gyrotron

$$\omega \approx \omega_H$$



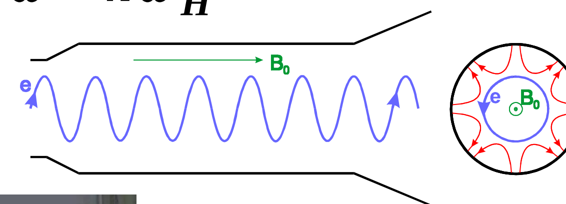
Magnetic field - 35.6 T
Accelerating voltage - 30 kV
Beam current - 5A
Operating mode - $TE_{17,4}$

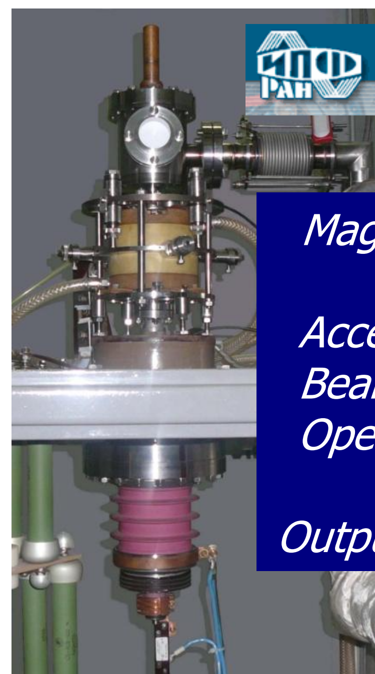
Output power ~ 5 kW

Bratman V. et al Inst. of Applied Physics RAS, Russia

Large orbit gyrotron (LOG)

$$\omega \approx n\omega_H$$

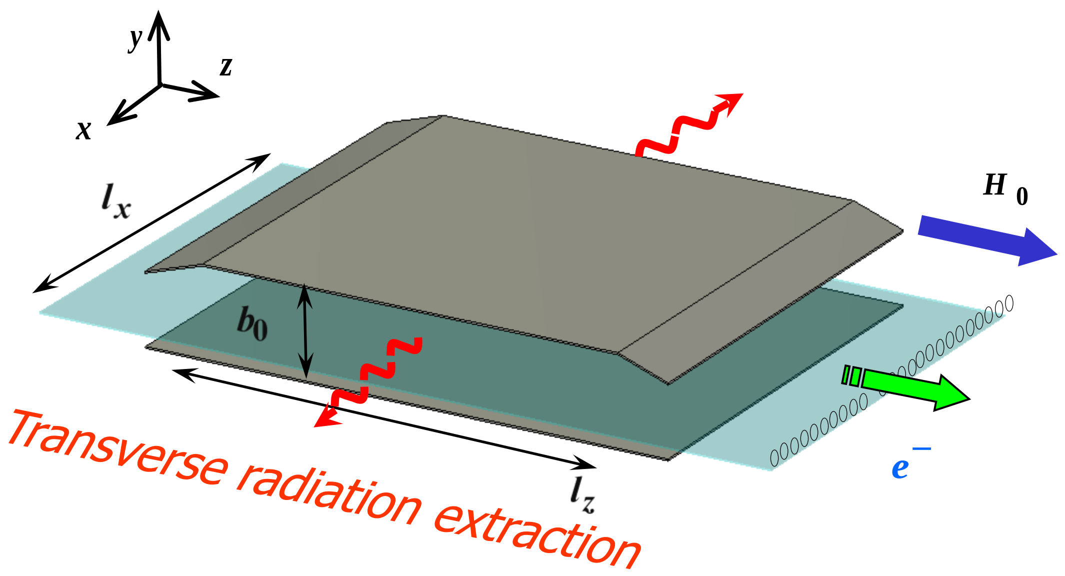


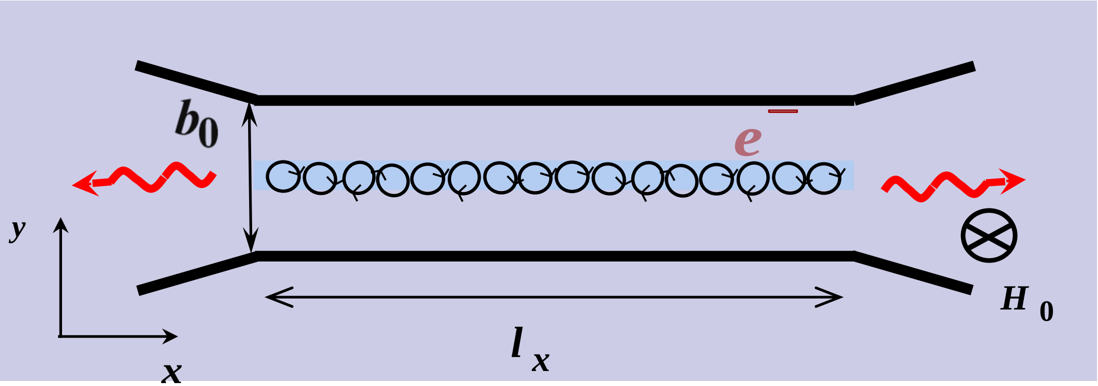


Magnetic field - 12 T
n=3
Accelerating voltage - 80 kV
Beam current - 0.7 A
Operating mode - $TE_{3.6}$

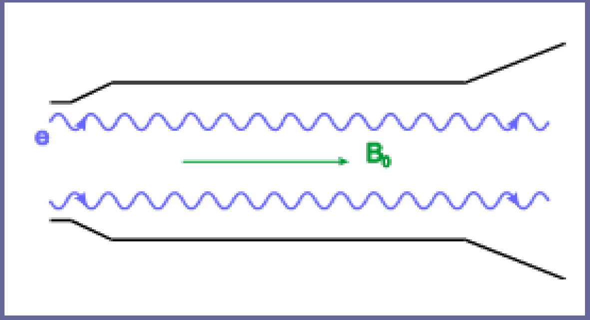
Output power ~ 0.5 kW

Scheme of planar gyrotron with transverse diffractional energy extraction



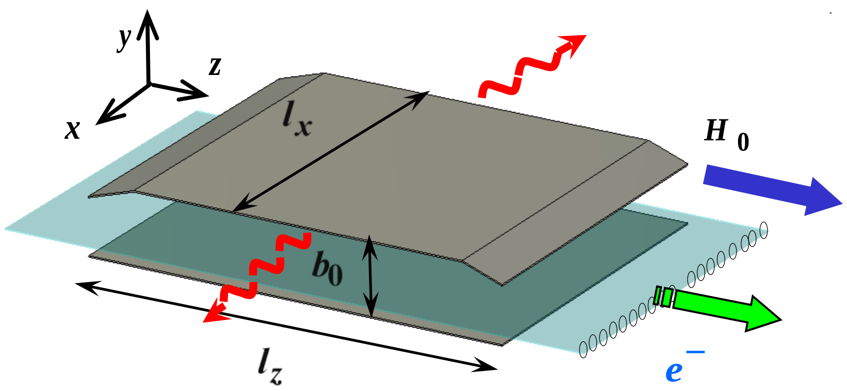


Conventional gyrotron scheme



Diffractional mechanism of energy extraction takes place along longitudinal coordinate

Selection mechanism in planar scheme of gyrotron



Longitudinal coordinate z

- electronic mechanism caused by shifting of zone of cyclotron resonance mismatch for modes with different longitudinal indexes

Transverse coordinate y

$$\frac{c\pi}{b_0} > \frac{\omega}{N}$$

$N = \omega_H l_z / 2\pi V_{||0}$ ***is number of cyclotron oscillations***

$$b_0 \le N\lambda$$

Open transverse coordinate x

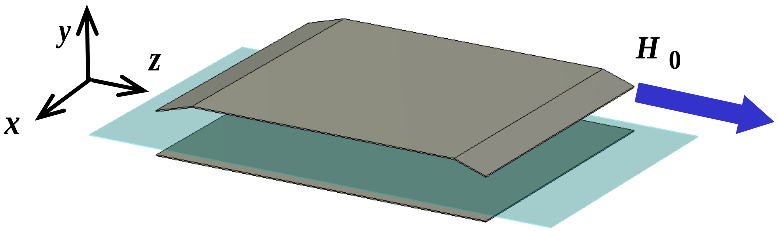
- electrodynamical mechanism of mode selection due to difference in diffraction losses for modes with different number of variations.

Cylindrical resonator of conventional gyrotron

$$\Delta\omega = \frac{1}{\omega}\frac{\pi c^2}{S} > \frac{\omega}{N}$$

$$R < \frac{\sqrt{N\lambda}}{2\pi}$$

Basic equations



$$\vec{E} = \vec{x}_0 \,\mathrm{Re}\left\{A(x,z,t)\sin\left(\pi s y / b_0\right) e^{i\omega_c t}\right\}$$

s *- mode number*

$$p = \left(p_x + i p_y\right)\exp\left(i\omega_c t\right) / p_{\perp 0}$$

$$\tau = \omega_c t \frac{\beta_{\perp 0}^4}{8\beta_{||0}^2} \qquad Z = \pi \frac{\beta_{\perp 0}^2}{\beta_{||0}} \frac{z}{\lambda}$$

$$X = \pi \frac{\beta_{\perp 0}^2}{\beta_{||0}} \frac{x}{\lambda} \qquad a = \frac{eA}{m \omega_c c \beta_{\perp 0}^3 \gamma_0}$$

$$i\frac{\partial^2 a}{\partial Z^2} + i\frac{\partial^2 a}{\partial X^2} + \frac{\partial a}{\partial \tau} + \sigma a = F(X) G J$$

$$\frac{dp}{dZ} + ip\left(\Delta - 1 + |p|^2\right) = -a \qquad J = \frac{1}{\pi}\int_0^{2\pi} p\, d\theta_0$$

$$p(Z = 0) = \exp(i\theta_0), \quad \theta_0 \in [0, 2\pi]$$

$$G = \frac{4}{\pi} \frac{e j_0}{m c^3} \frac{\lambda^2}{b_0} \frac{\beta_{||0}}{\beta_{\perp 0}^6 \gamma_0}$$

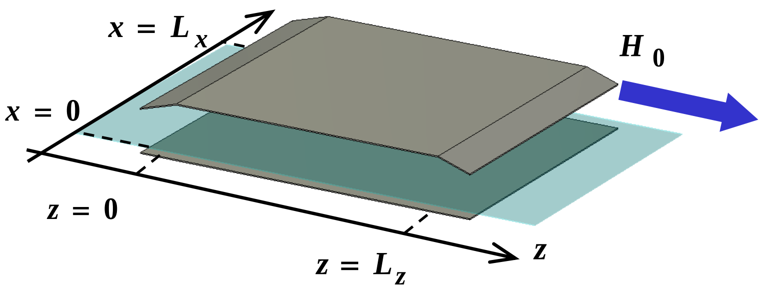
$$\sigma = \frac{\delta}{b_0} \frac{8\beta_{||0}^2}{\beta_{\perp 0}^4}$$

δ ***- skin depth***

$$\Delta = \frac{2}{\beta_{\perp 0}^2} \frac{\omega_c - \omega_H}{\omega_c}$$

- mismatch of cyclotron resonance

Expansion in the Fourier series



$$a(Z=0)=a(Z=L_z)=0$$

$$a=\sum_{n=1}^{\infty} a_n(X,\tau)\sin\frac{n\pi}{L_z}Z$$

$$-i\upsilon_n a_n + i\frac{\partial^2 a_n}{\partial X^2}+\frac{\partial a_n}{\partial \tau}+\sigma a_n = F(X)\frac{G}{L_z}\int_0^{L_z} J\sin\frac{n\pi}{L_z}dZ$$

$$\frac{dp}{dZ}+ip\left(\Delta-1+|p|^2\right)=-\sum_{n=1}^{\infty} a_n(X,\tau)\sin\frac{n\pi}{L_z}Z$$

Standard gyrotron equations

$$i\frac{\partial^2 a}{\partial Z^2}+\frac{\partial a}{\partial \tau}=GJ$$

$$\frac{dp}{dZ}+ip\left(\Delta-1+|p|^2\right)=-a$$

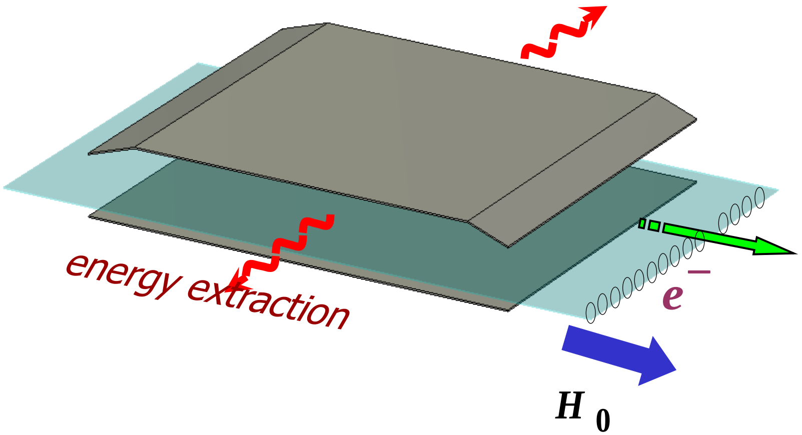
Radiation boundary conditions

$$a_n(X=0,L_x;\tau)\pm$$
$$\pm\frac{1}{\sqrt{\pi i}}\int_0^{\tau}\frac{e^{-(\sigma-i\upsilon_n)(\tau-\tau')}}{\sqrt{\tau-\tau'}}\left.\frac{\partial a_n(X,\tau')}{\partial X}\right|_{X=0,L_x}d\tau'=0$$

$$\upsilon_n=\left(n\pi/L_z\right)^2$$

Parameters of submillimeter planar gyrotron used for simulations

Operating frequency	*~1 THz*
Accelerating voltage	*30 кV*
Pitch-factor	*~1*
Linear current density	*40 A/cm*
Distance between plates	*1 cm* ~ 30λ



$$G = \frac{4}{\pi}\frac{ej_0}{mc^3}\frac{\lambda^2}{b_0}\frac{\beta_{||0}}{\beta_{\perp 0}^6\gamma_0}$$

- current parameter

$$G \approx 0.004$$

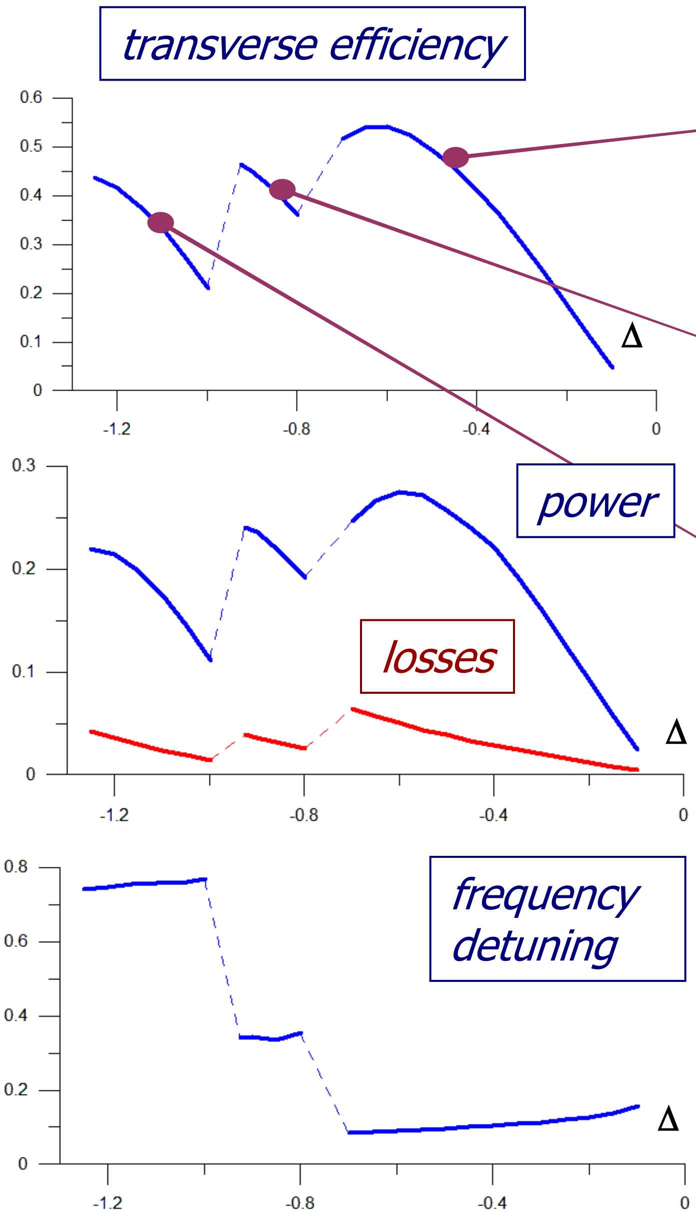
$$\sigma \approx 0.0015$$

$$\sigma = \frac{\delta}{b_0}\frac{8\beta_{||0}^2}{\beta_{\perp 0}^4}$$

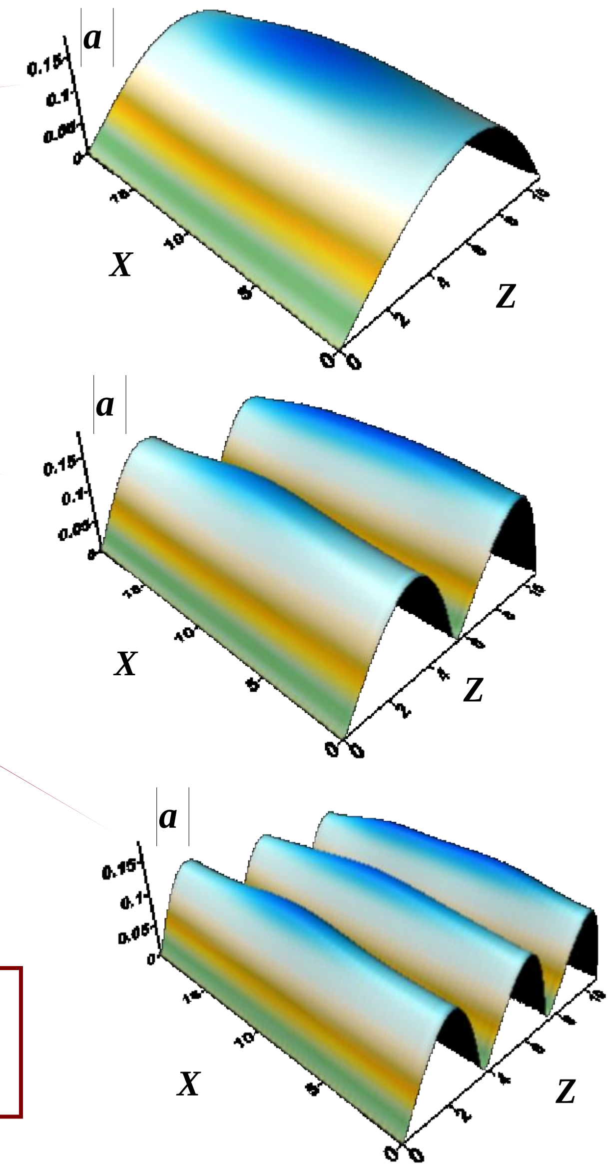
- losses parameter

δ ***is the skin depth***

Main zones of stationary generation corresponding to excitation of modes with different number of longitudinal variations



$$\Delta = \frac{2}{\beta_{\perp 0}^{2}} \frac{\omega_c - \omega_H}{\omega_c}$$



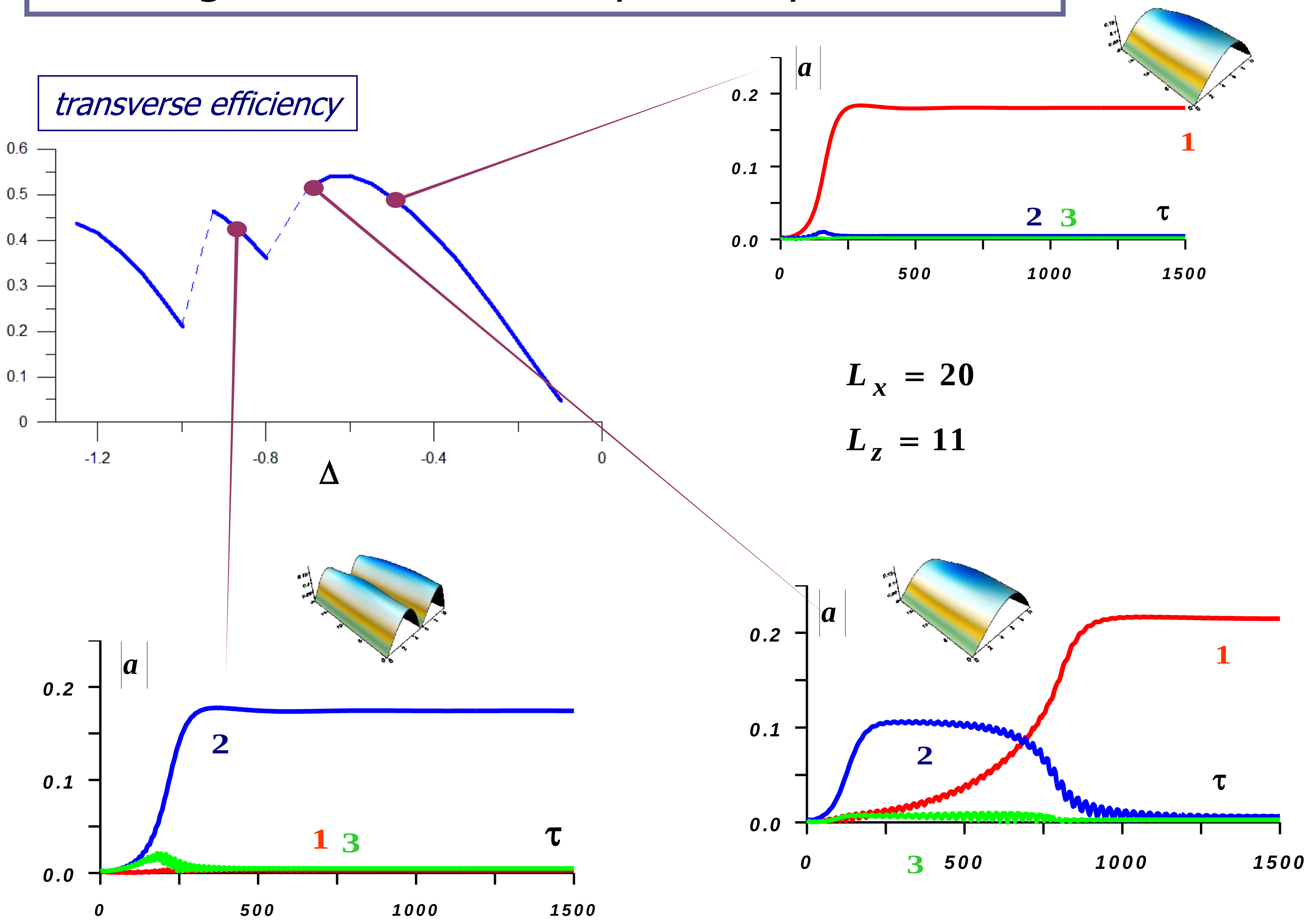
$L_x = 20$

$L_z = 11$

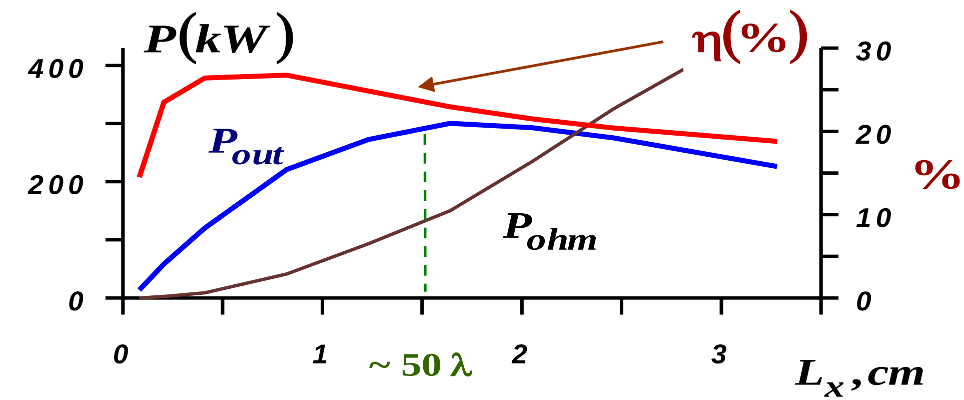
$G \approx 0.004$

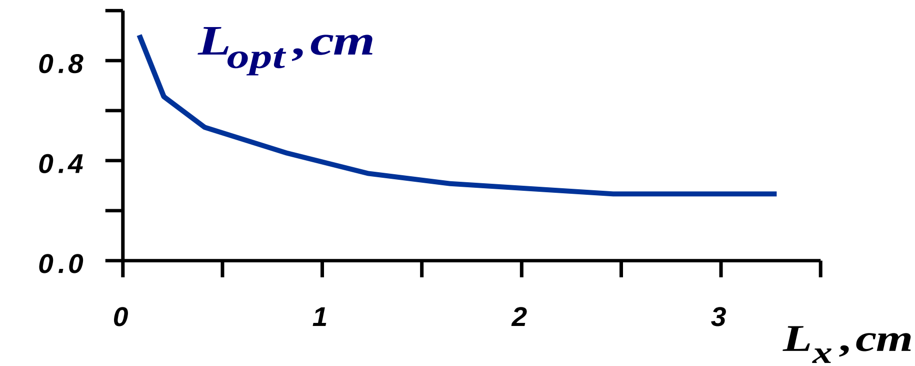
$\sigma \approx 0.0015$

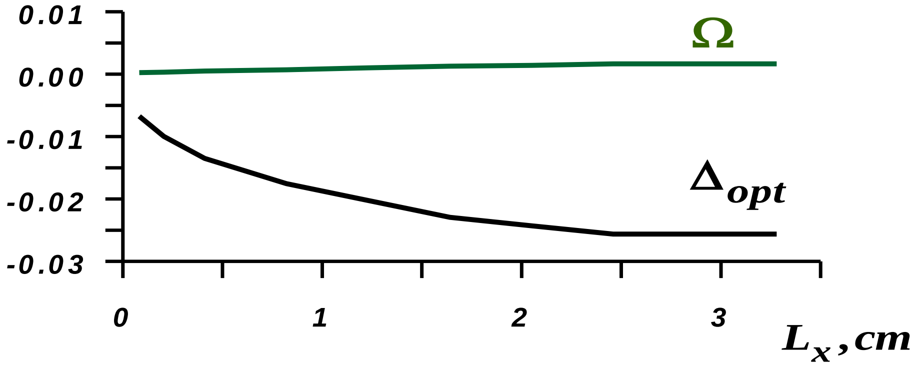
The longitudinal mode competition patterns.



Parameters of steady-state regime vs gyrotron transverse size Lx





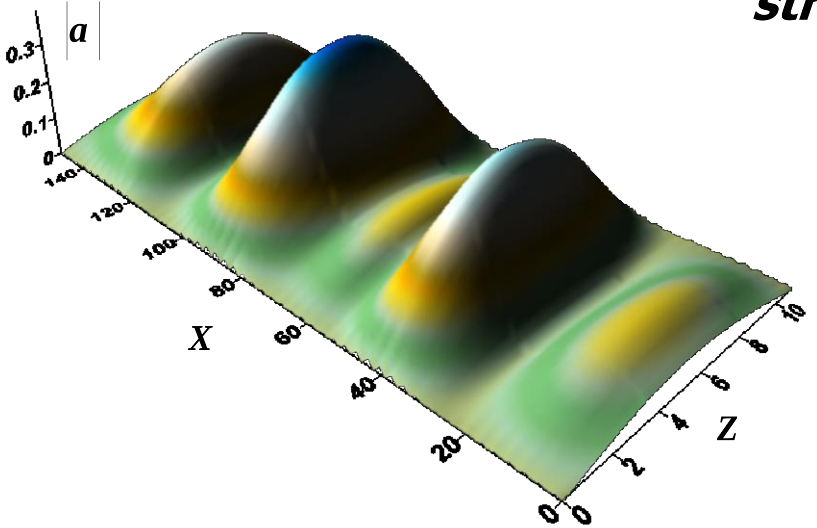


Parameters of simulations

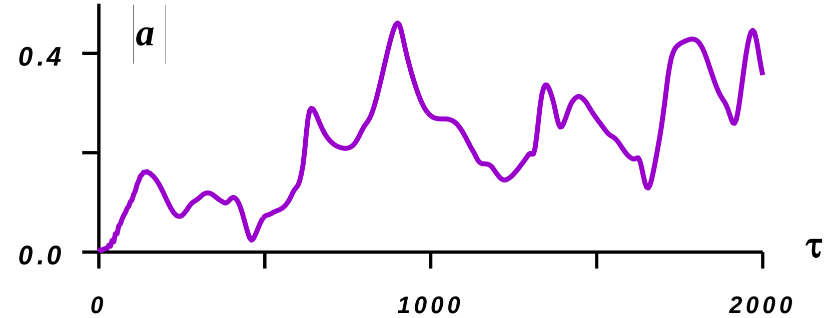
Operating frequency	~1 THz
Accelerating voltage	30 кV
Linear current density	40 A/cm
Pitch-factor	~1
Distance between plates	1 cm

Optimal width	1.5 cm
Optimal length	0.46 cm
Efficiency	~ 26 %
Output power	~ 300 kW
Losses	~ 30 %

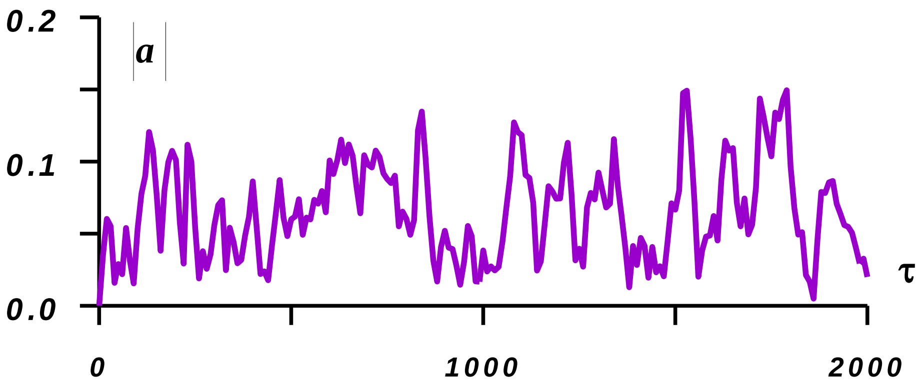
$L_x = 120\lambda,\ L_z = 15\lambda$

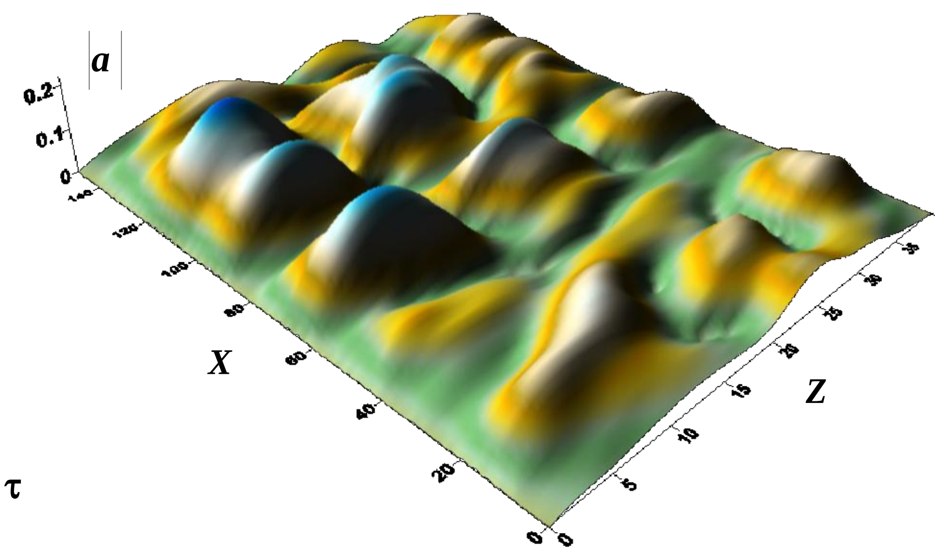


Complication of transverse radiation structure with increasing of the beam width



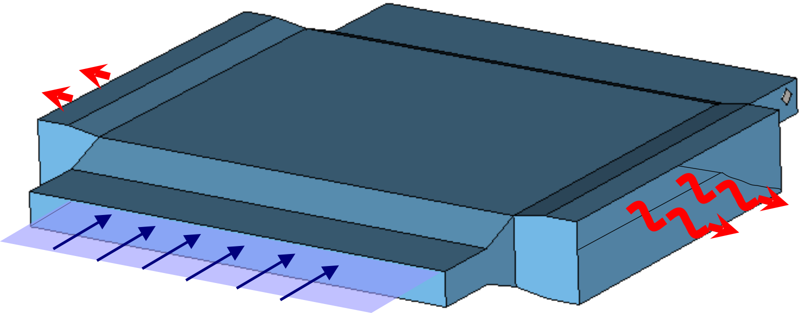
Two-dimensional chaotic behavior



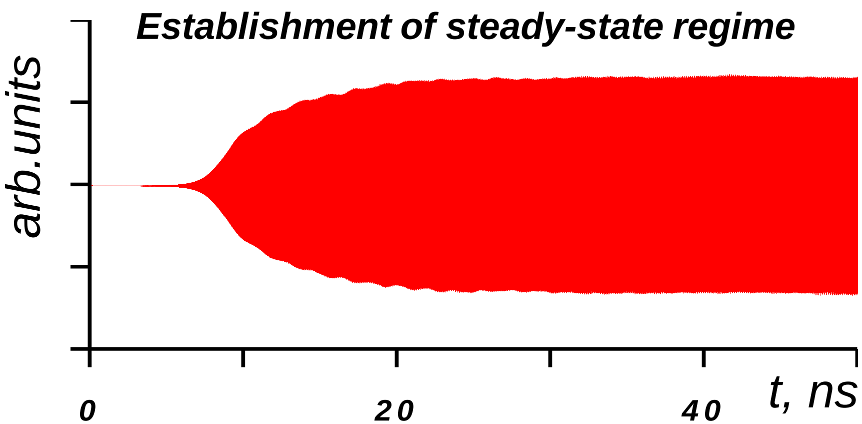


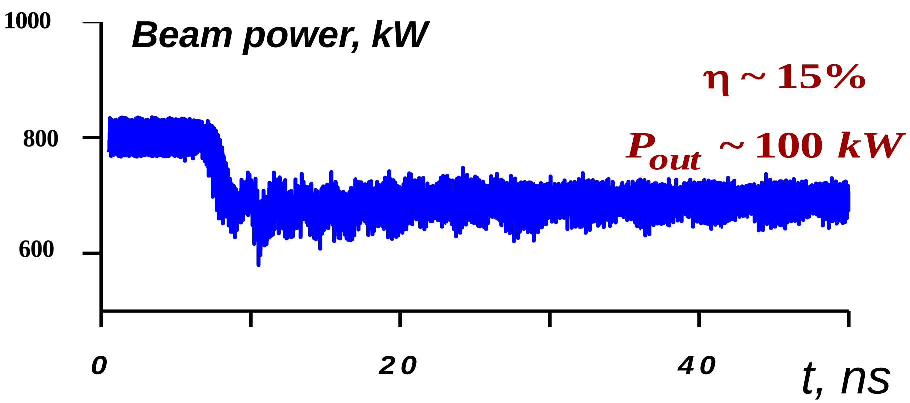
$L_x = 120\lambda,\ L_z = 60\lambda$

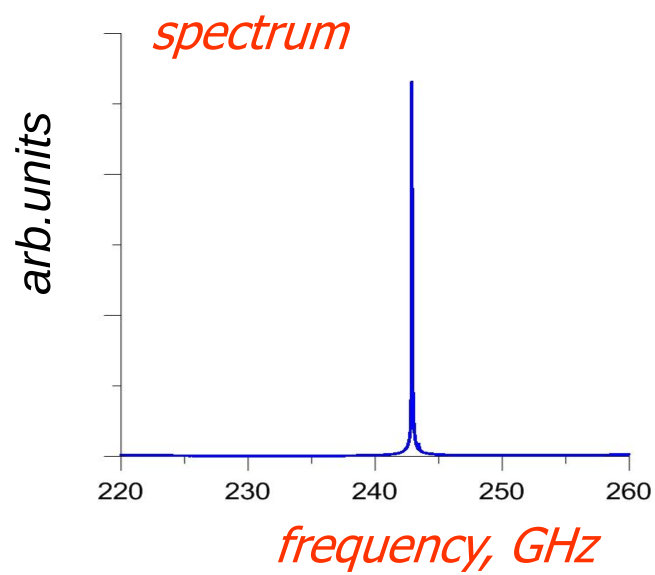
3D simulations of 240 GHz planar gyrotron



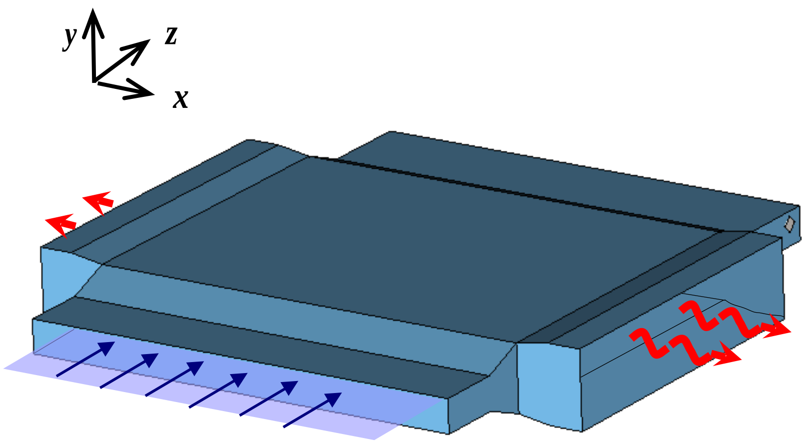
Guiding magnetic field	10.1 T
Electron current	10 A
Accelerating Voltage	80 kV
Pitch-factor	~1
Resonator width	20 mm
Resonator length	15 mm
Gap between plates	3 mm



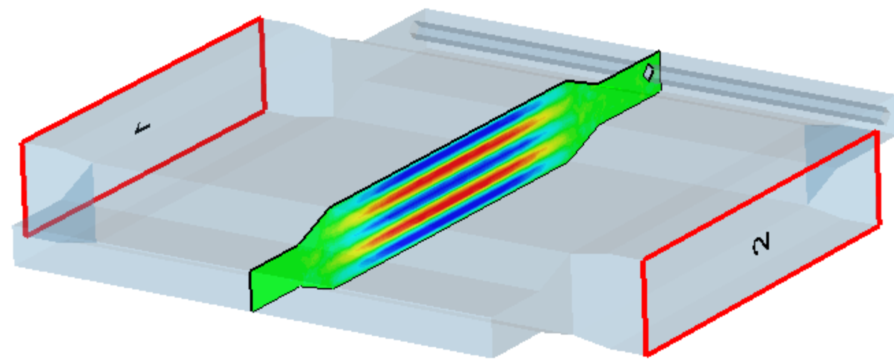




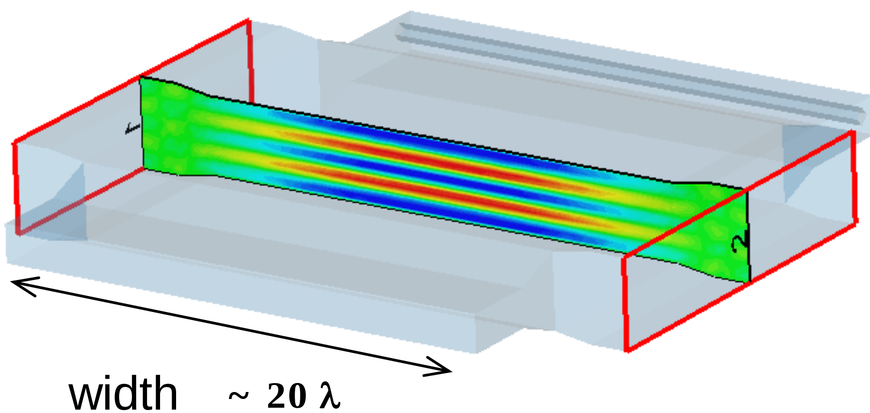
3D simulations of 240 GHz planar gyrotron

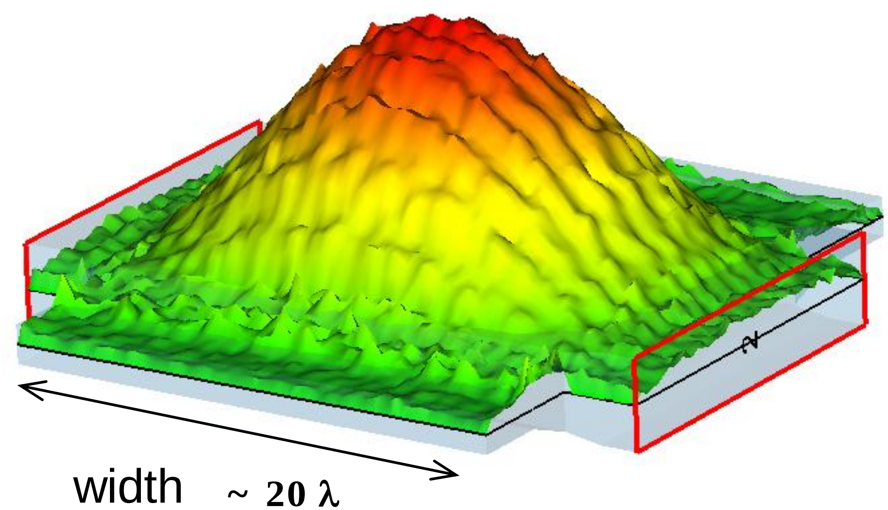


Longitudinal structure of Ex field component

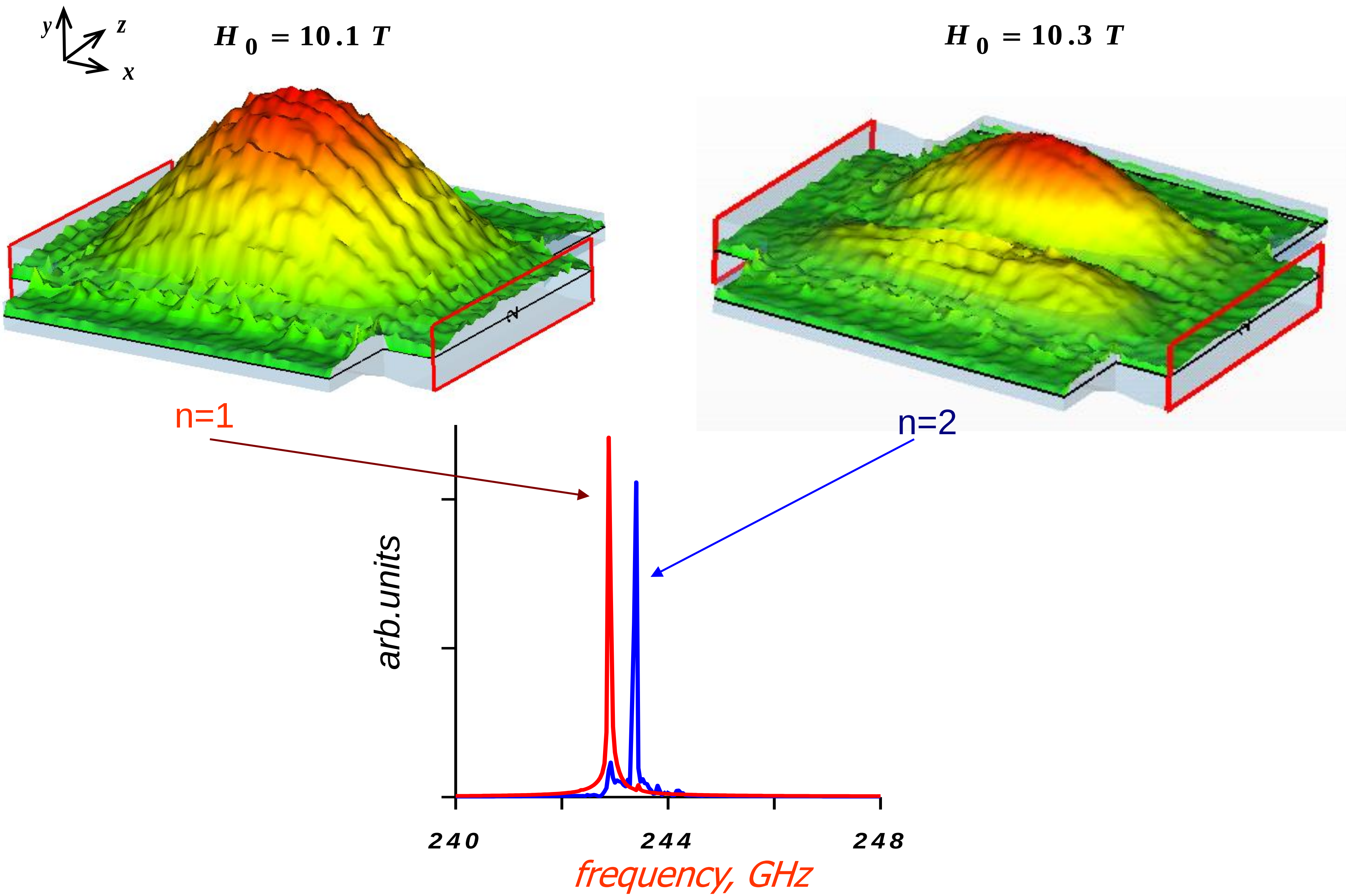


Transverse structure of Ex field component





3D simulations of 240 GHz planar gyrotron



Conclusion

1. For increasing of integral power of short wavelength gyrotrons up to level of several hundred kilowatts the planar scheme of gyroton with transverse energy extraction is suggested.

2. Analysis of nonlinear dynamics in the frame of time domain approach demonstrates effective mode selection over longitudinal and both transverse coordinates.

3 Results of averaged approach are partially supported results of direct pic code simulaltions

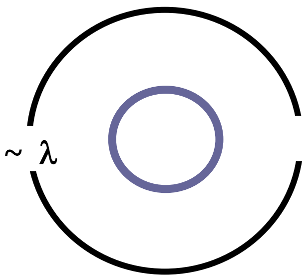
Evolution of conception of gyrotron with side slits

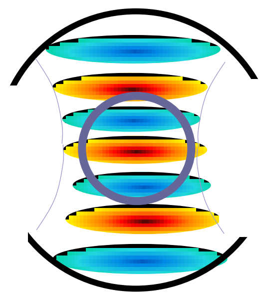
(transformation of slits originally used for transverse mode selection to main channel of diffractional energy extraction)

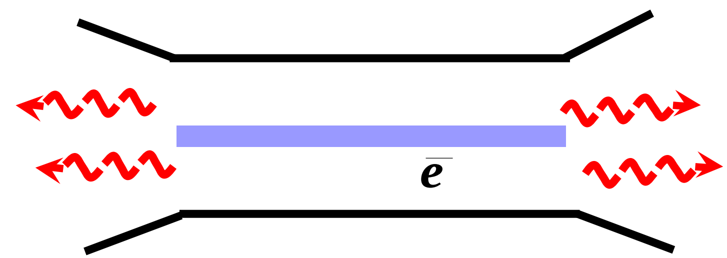
Gyrotron with longitudinal side slis

Confocal quasi-optical gyrotron

Planar gyrotron with transverse energy extraction

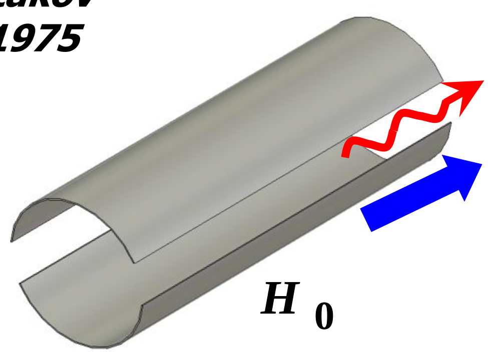


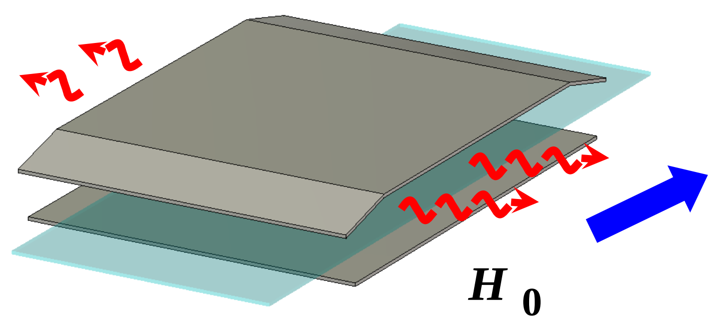




I.I.Antakov et al, 1975

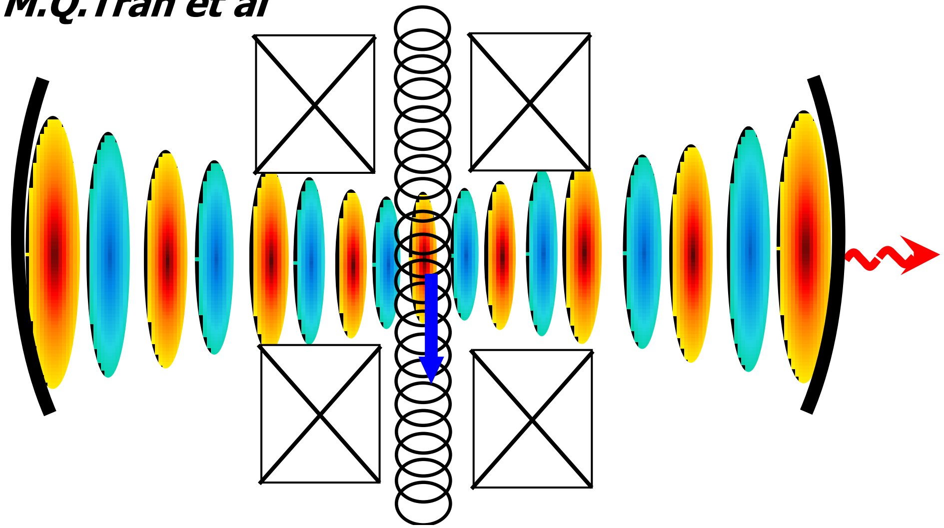
R.J.Temkin et al





Quasi-optical gyrotrons

M.Q.Tran et al



- ***energy extraction in transverse direction by 2 counter-propagating wave with group velocity close to c***
- ***absence of mode selection on transverse coordinate***
- ***bulky m.w. system***