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# Synchronization in Microwave Electronics

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## History of problems

- Christiaan Huygens
  - A.A. Andronov
  - I.I. Blekhman,
  - V.D. Shalffeev
  - K. Kaneko
  - V.S. Anishchenko
  - M. Rosenblum
  - B. Van der Pol
  - R. Adler
  - A.N. Malakhov
  - P.S. Landa
  - S.P. Kuznetsov
  - A. Pikovskii
  - J. Kurths
  - et al.
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## Significance of study of external signal influence on electron-wave spatially distributed systems

- Stabilization of frequency and phase
- Wideband noise non-autonomous generation
- Increase power and efficiency of generation
- Phase array on high-power microwave sources
- Fundamental aspects of synchronization of distributed systems

## History of problems. UHF Electronics.

- R.V. Khohlov, Mutual synchronization of two coupled **klystron** (1956-1959): increasing of bandwidth of frequency tuning
- Synchronization of **magnetron generators**:
  - Dayvid, 1961
  - V.D. Shalfeef, 1970 980
- Synchronization of **backward-wave oscillator**  
O and M type: simple stationary theory and some experimental results:
  - M.J. Wong, G.D. Sims, I.M. Stephenson, 1961;
  - V.I. Kanavets, 1961;
  - G.P. Rapoport, 1964;
  - E.E. Gelezovskii, E.V. Kal'janov, 1965, 1973;
  - V.A. Solntsev, 1966.

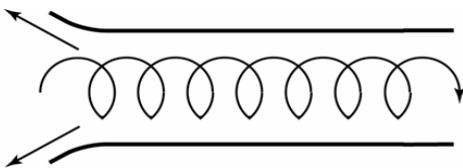
## Why electron systems with distributed interaction cause interest?

«Fast» effect on active electron-wave system in short impact regime of generation:

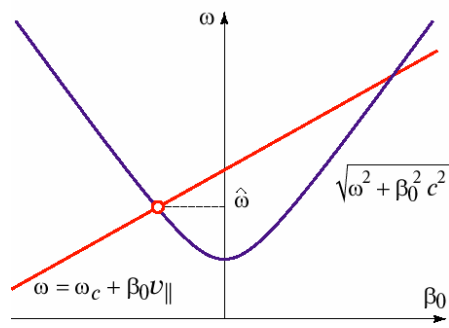
$$T = \frac{Q}{4\pi f} \sqrt{P_0/P_{ext}} \quad \text{- response time on external action,}$$

where  $Q$  is quality of electrodynamic system,  $f$  is frequency of signal,  $P_0$  and  $P_{ext}$  are effective device power and external signal power

## Synchronization of gyrotron backward-wave oscillator: results of non-stationary theory



Dispersion characteristics of electromagnetic waveguide mode and electron beam



Mathematical model of interaction of spiral electron beam with backward electromagnetic wave:

$$\frac{d\beta}{d\xi} - j\mu(1 - |\beta|^2)\beta = F, \quad \frac{\partial F}{\partial \tau} - \frac{\partial F}{\partial \xi} = -\frac{1}{2\pi} \int_0^{2\pi} \beta d\theta_0$$

$$F(\tau = 0) = f^0(\xi), \quad \beta(\xi = 0) = \exp(j\theta), \quad \theta \in [0, 2\pi],$$

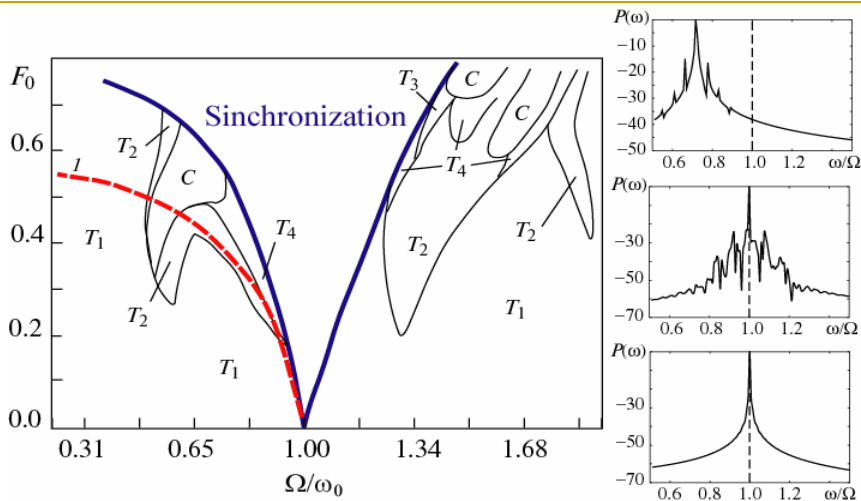
External harmonic field:

$$F(\xi = A, \tau) = F_0 \exp(j\Omega \tau)$$

$A$  is non-dimensionless length of distributed system;

$\mu$  is non-isochronism parameter of electron-oscillator;

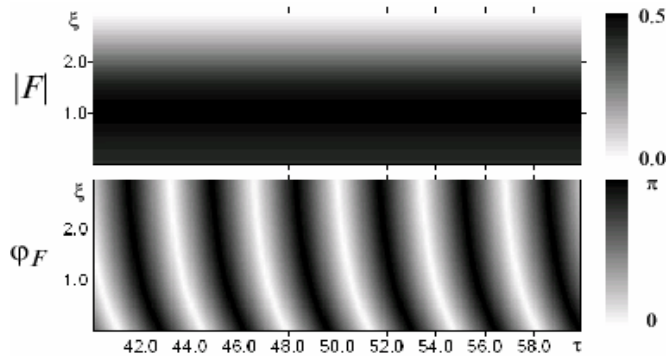
$F_0$  and  $\Omega$  is amplitude and frequency of external field.



Non-autonomous regimes gyro-BWO reproduced on parameter plane "frequency – amplitude external signal". Output signal power spectra are presented to the right for following oscillations regimes: non-synchronization (top), synchronization (bottom), quasi-synchronization (center)

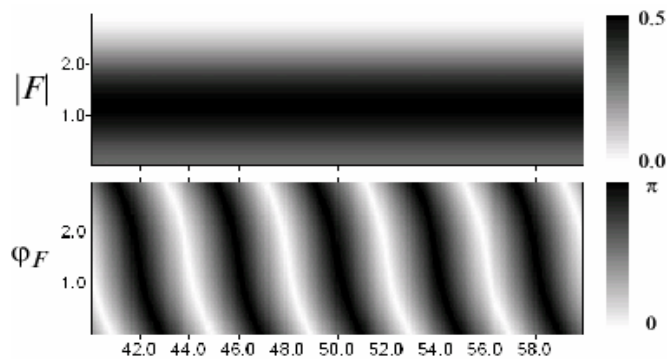
## Physical processes and space dynamics in gyro-BWO with external field

### ■ Autonomous dynamics



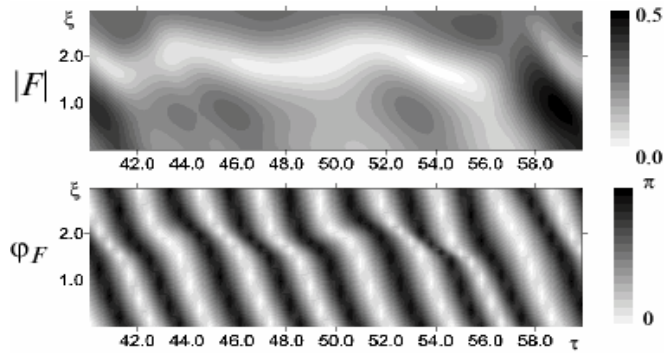
## Physical processes and space dynamics in gyro-BWO with external field

### ■ Synchronization regime



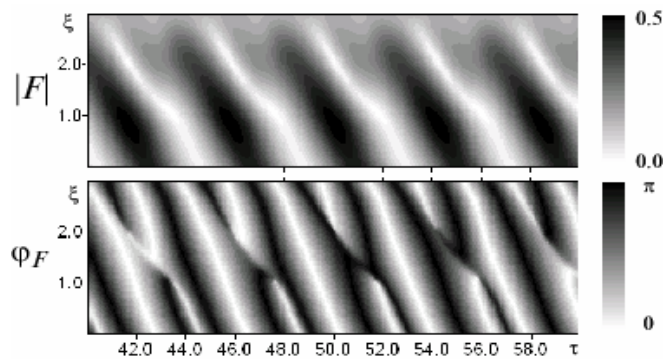
## Physical processes and space dynamics in gyro-BWO with external field

### ■ Quasi-Synchronization regime



## Physical processes and space dynamics in gyro-BWO with external field

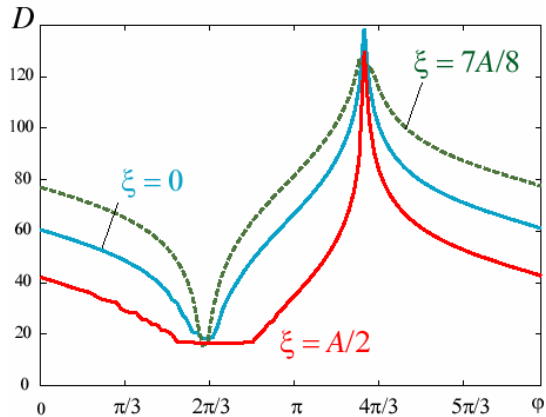
### ■ Non-synchronization regime



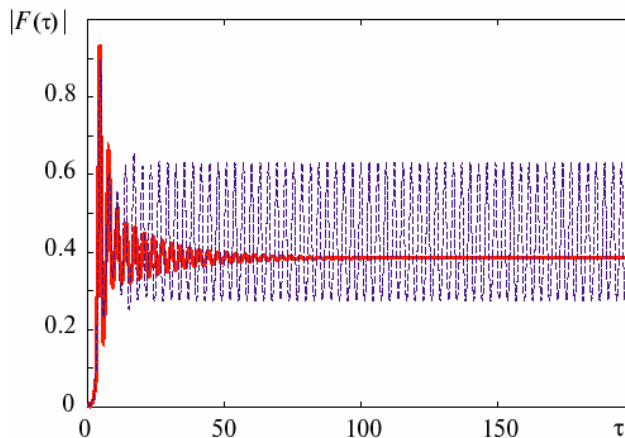
## Time of stabilization of synchronization in the distributed active media

External field:

$$F(\xi = A, \tau) = F_0 e^{j(\Omega\tau + \varphi)}$$

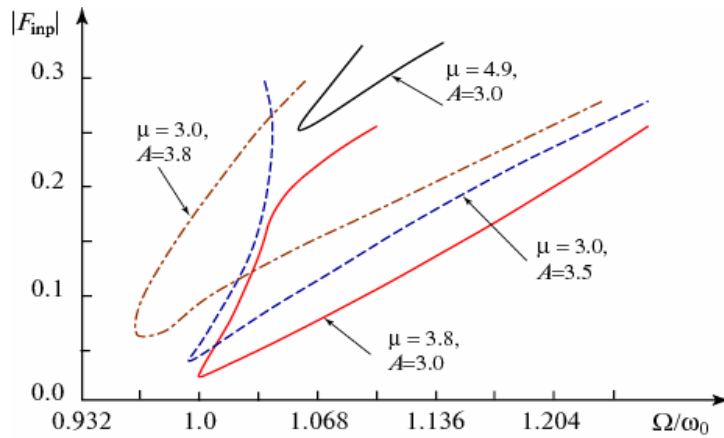


## Suppression of automodulation by the external signal

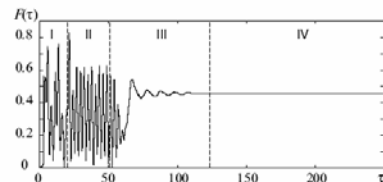
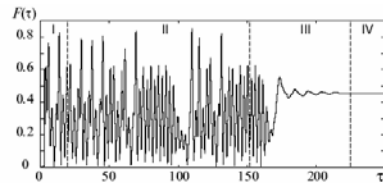
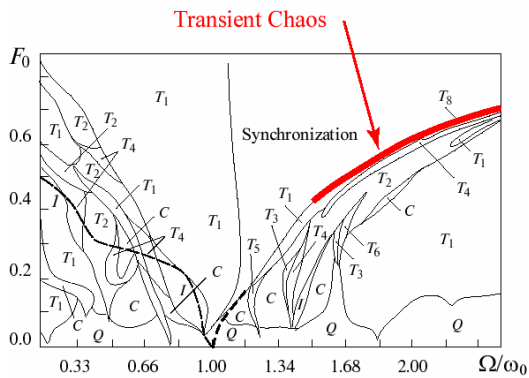


Time realization of output field in automodulation regime of gyro-BWO and typical time realization non-autonomous system in stationary regime generation

## Automodulation suppression region on parameter plane “frequency – amplitude external signal”



## Transient chaos close to synchronization region





# Experimental study of synchronization gyro-BWO

- Kou C.S., Chen S.H., Barnett L.R., Chen H.Y., Chu K.R.  
Experimental study of an injection-locked gyrotron backward-wave oscillator // Phys. Rev. Lett. **70** (1993) 924

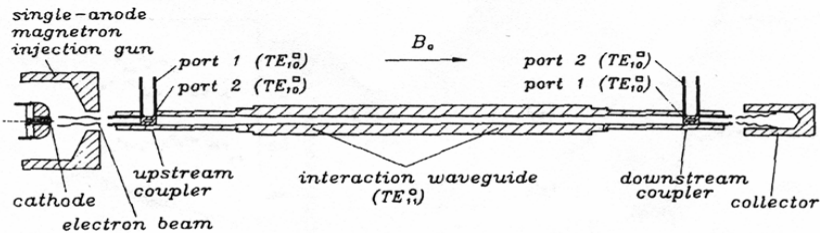


FIG. 2. Schematic of the gyro-BWO.

## Experiment

Characteristics of gyro-BWO	
Beam voltage	$V_0=100$ kV
Beam current	$I_0=5.8$ A
Generation frequency	34 GHz
$v_{\perp}/v_{\parallel}$	0.9
Magnetic field	14.52 kG
Efficiency	~20%
Output power	$P_{\text{BWX}}=97.5$ kW
Synchronization regime	
Input signal power	$P_{\text{BX}} = 2.7$ kW $P_{\text{BX}}/P_{\text{BWX}} = 0.028$
<b>Synchronization bandwidth</b>	<b><math>\Delta f &gt; 100</math> MHz</b> $\Delta f/f \sim 0.3\%$

## Theory

Generation frequency

$$f_0 = 34 \text{ GHz}$$

Synchronization bandwidth

$$\Delta\Omega \sim 1.07$$

Synchronization bandwidth in dimensionless parameters

$$\Delta f \sim 150 \text{ GHz}$$

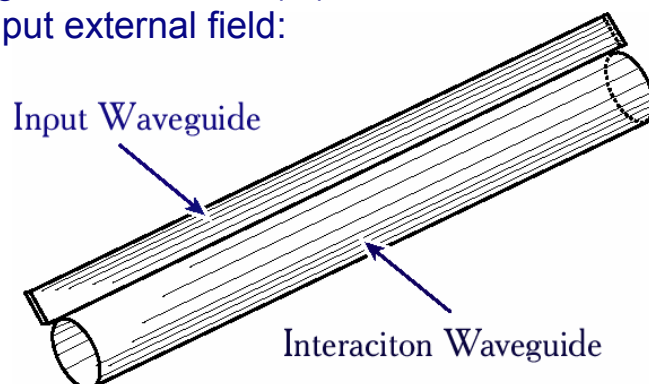
## Base features of non-autonomous regimes in distributed active media

- Appearance of quasi-synchronization regimes (complication of output signal power spectrum of the auto-oscillation medium)
- Complication of space dynamics of non-autonomous distributed system (in the interaction space there appear the regions where synchronization occurs and where it's destroyed)

How to broaden the synchronization bandwidth and get rid of the complex power spectrum of radiation?

## Distributed input of an external signal to the interaction space of gyro-BWO

Coupled waveguide structures (!!!)  
for allocated input external field:

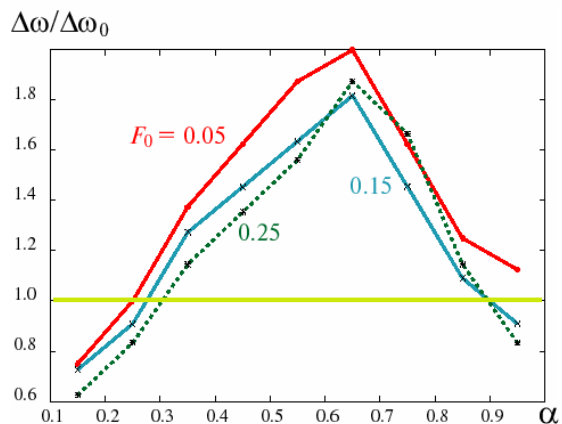


## Theory of gyro-devices with fast electromagnetic waves and coupled electrodynamic systems

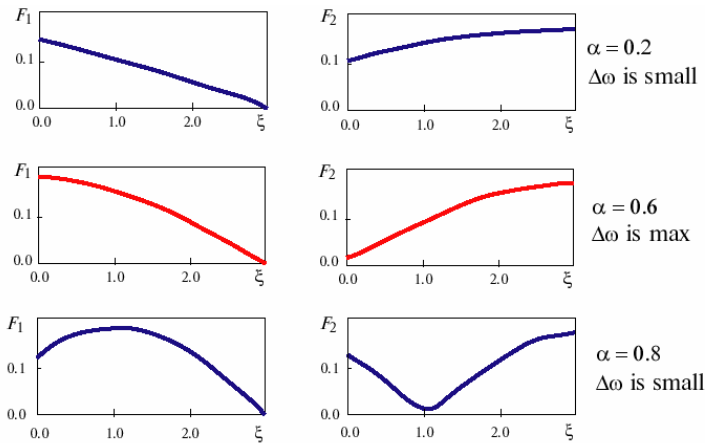
- *Koronovskii, A.A., Trubetskov, D.I., Hramov, A.E.*  
Investigation of oscillations in gyro-generator with backward wave and coupled electrodynamic systems. *Tech.Physics*. 2003. **73**(6) 110—117

## Bandwidth of synchronization for distributed input external field

$\alpha$  is coupling coefficient between coupled waveguide structures;  
 $\Delta\omega_0$  is bandwidth of synchronization for located input signal in gyro-BWO in collector end of tube



## Field distributions in cold coupled waveguide systems for different $\alpha$

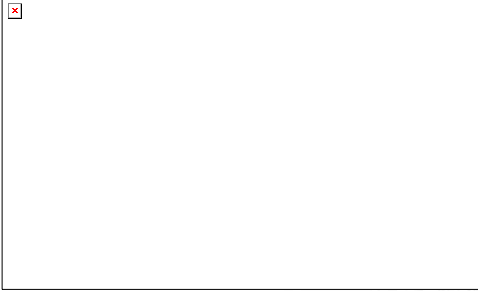


## Synchronization of Virtual Cathode Oscillations

### Experimental study of influence external field on virtual cathode oscillators

- Grigor'ev V.P. et al. On possibility frequency change by the external signal in UHF-triode with virtual cathode // Tech.Phys.Lett. 1988 **14** 2164
- K. Hendricks, R. Adler, R. Noggle. Experimental results of phase locking two virtual cathode oscillators // J. Appl. Phys. 1990 **68**(2) 820
- H. Sze, D. Price, B. Harteneck. Phase locking of two strongly coupled vircators // J. Appl. Phys. 1990 **67**(5) 2278

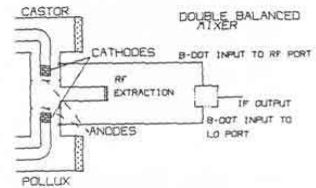
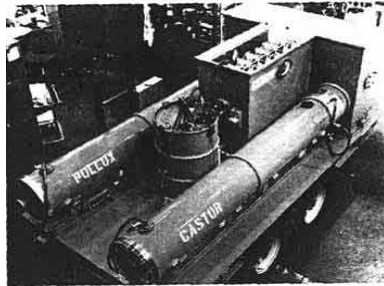
## Different experimental setup of coupling vircators



H. Sze et al

Results of phase locking:

$$\Delta f < 10 \text{ MHz}$$
$$|\Delta\phi| \sim 25\%$$

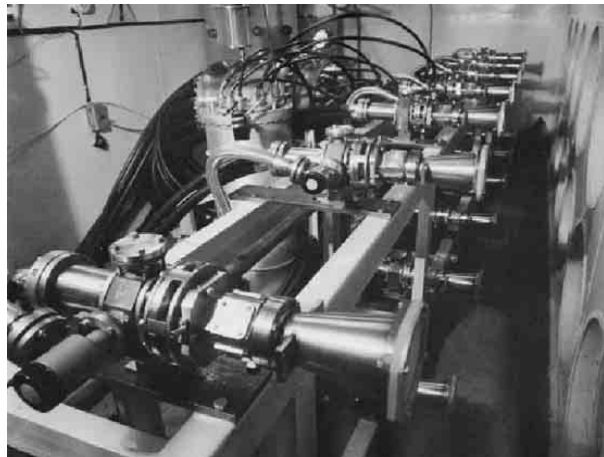


K. Hendricks et al

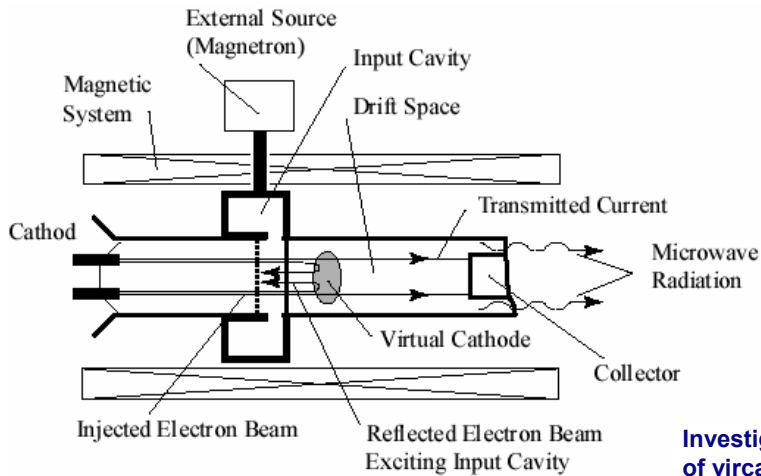
## Phased array on vircators

*Selemir V.D., Dubinov A.E.*  
Electron devices with virtual  
cathode // J. Comm. Techn.  
Electron. 2002. 47(6) 575

Phased Array named  
“Fregat” constructed from 14  
vircators, which controlling  
by one high power  
microwave sources



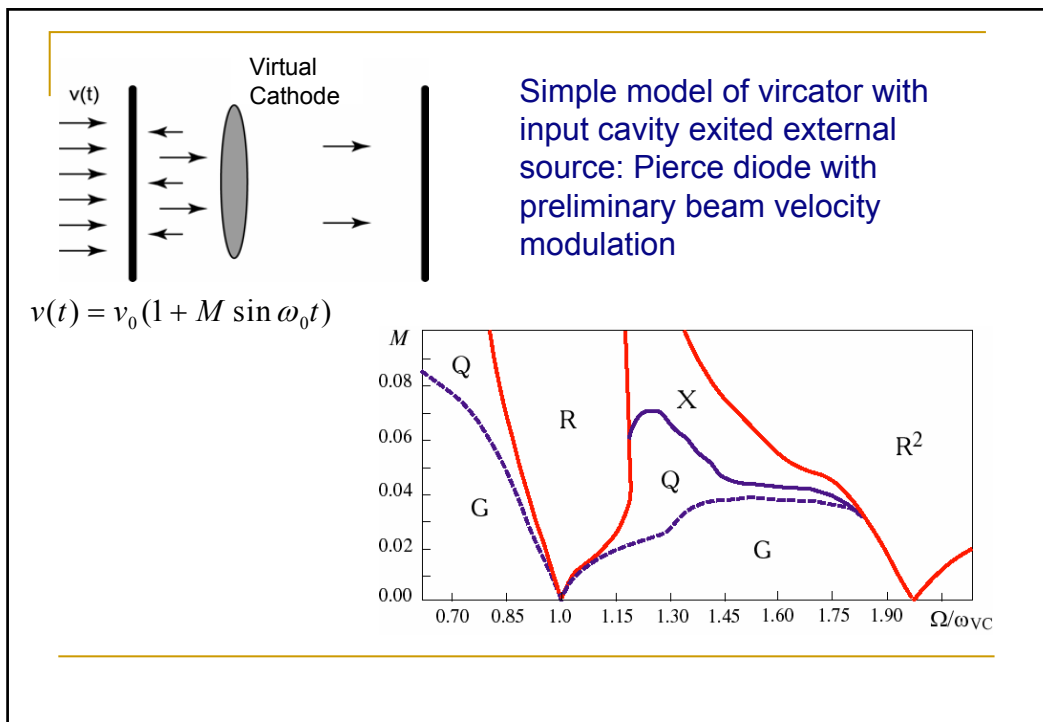
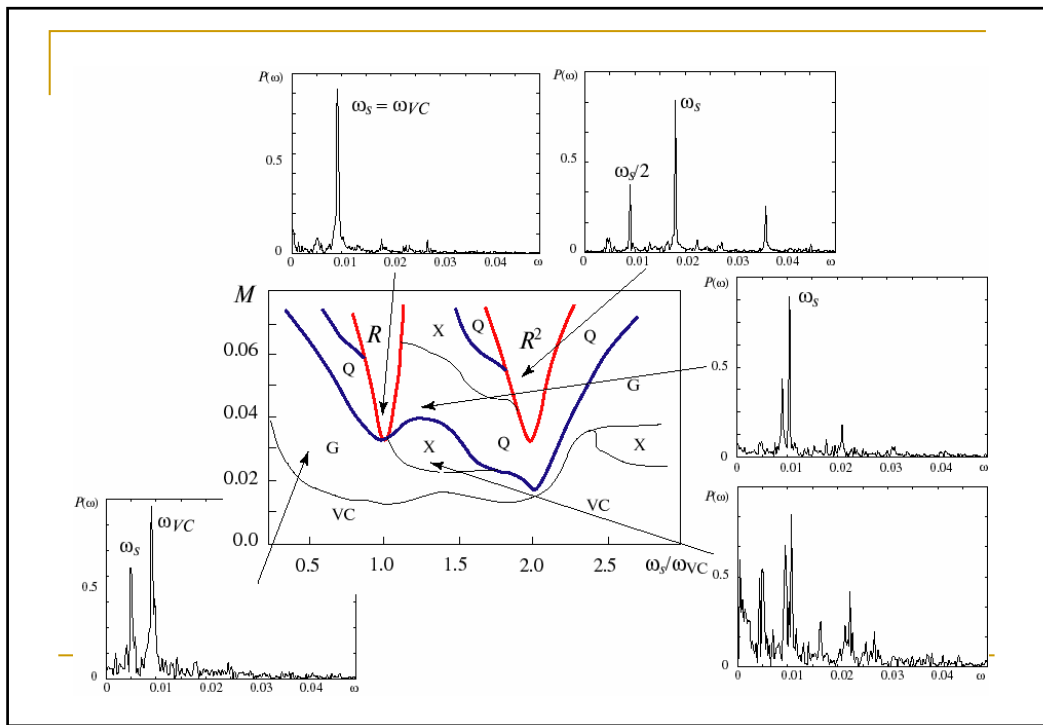
## Numerical study of external modulation of electron beam on virtual cathode oscillators



**Investigated scheme  
of vircator with  
preliminary beam  
modulation**

## Experiments on modulation of intense relativistic electron beam

- *Friedman M., Serlin V.* Modulation of intense relativistic electron beams by an external microwave sources. *Phys.Rev.Lett.* 1985. **55(26)** 2860
- *Friedman M., Krall J., Lau Y.Y., Serlin V.* Externally modulated intense relativistic electron beams. *J.Appl.Phys.* 1988. **64(7)** 3353



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## Summary

- Appearance of non-autonomous regimes with trapping of generation ultra-high frequency in the presence of complex low-frequency oscillations of field amplitude (quasi-synchronization regimes)
  - Complex space-time dynamics of electron beam in anisochronous regimes of distributed electron-wave media with backward electromagnetic wave
  - Availability of transient chaos near boundary of synchronization area
  - Suppression of self-modulation of output signal of electron-wave media with backward electromagnetic wave
  - “Super fast” synchronization of distributed active media
  - Broaden the synchronization bandwidth and get rid of the complex power spectrum of radiation by the distributed input of external signal with the aid of coupled waveguide structures
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