MICROWAVE SOURCES FOR 3-rd AND 4-th GENERATION OF ECRIS

Yu. Bykov, G. Denisov, A. Eremeev, S. Samsonov

Institute of Applied Physics, Russian Academy of Sciences
46 Uljanov Str., Nizhny Novgorod, Russia
e-mail: byk@appl.sci-nnov.ru

Reported by **Vadim Skalyga**

ECRIS 2008 18th International Workshop on ECR Ion Sources
Chicago, Illinois USA - September 15 -18, 2008

According to current conceptions, the next generation of ECRIS will require microwave sources with

- operating frequency of 28 – 60 GHz, at least
- continuous wave power of tens kilowatts (10 – 30 kW),
- following options for operation
  - fast frequency sweeping (with a sweep time less than 10-4 s within a frequency band of few percents)
  - or generation of CW signal with broadband spectrum (few percents)
  - or multi-frequency generation.

It is generally recognized that the only microwave sources capable of delivering CW or average power of order of 10 kW in the frequency range of tens GHz are vacuum electron devices basing on the cyclotron resonance maser (CRM) instability and using low-relativistic electron beams (particle energy of about tens keV), often called as gyro-devices.

The operation of gyro-devices is based on interaction of electrons gyrating in the external magnetic field with fast electromagnetic wave under the cyclotron resonance condition

$$\omega - hv_{\|} \approx n\omega_{\mathrm{H}},$$

(ω and h are the frequency and the axial wavenumber of the wave, $v_{\|}$ and ω_{H} are the axial velocity and the cyclotron frequency of the electrons, n is the cyclotron harmonic number).

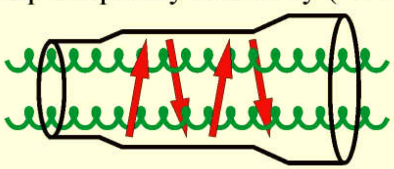
The interaction of electrons with fast electromagnetic waves propagating in the cavities and waveguides with smooth metal walls is the distinguishing feature of gyro-devices as opposed to conventional slow-wave electron devices.

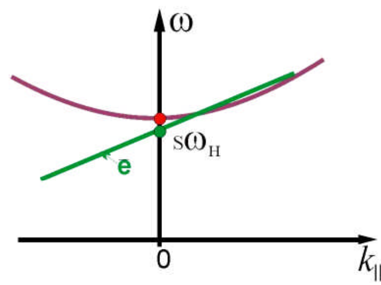
Since no periodic structure is employed, an enhanced power handling capability exists in gyro-devices.

GYRO-DEVICES

OSCILLATORS

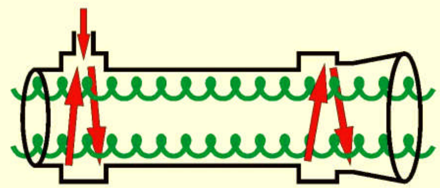
GYROTRON
- high efficiency (30-50%)
- narrow frequency bandwidth (~0.1%)
- step-frequency tunability (30-50%)



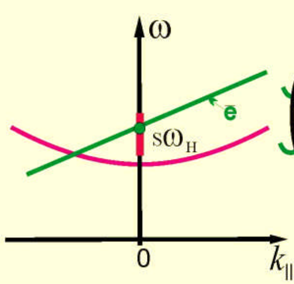


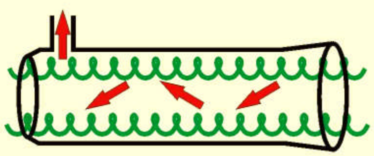
AMPLIFIERS

GYRO-KLYSTRON
- high efficiency (30-50%)
- frequency bandwidth < 1%

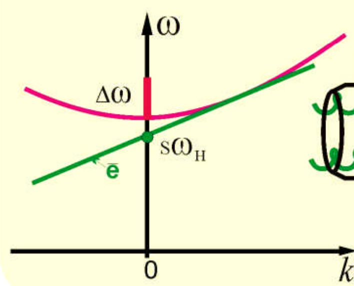


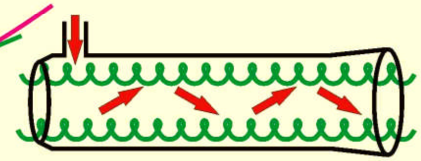
GYROTRON BACKWARD WAVE OSCILLATOR
GYRO-BWO
- broad smooth frequency-tunability (~10%)





GYROTRON TRAVELLING WAVE TUBE
GYRO-TWT
- broad smooth frequency-tunability (>10%)





$$\omega = s\omega_H + k_{\parallel} v_{\parallel}$$

Institute of Applied Physics, Russian Academy of Sciences

Gyrotron for ITER under development

GYROKLYSTRON

The development of the millimetre-wave Ka-band (34-36 GHz) and W-band (93-95 GHz) gyroklystrons was primarily stimulated by radar applications within the ranges of the atmospheric RF “windows”. Later, high power pulse gyroklystrons attracted attention as sources of coherent radiation for compact, high gradient linear accelerators.

Pulse 35 GHz two-cavity gyroklystron developed in IAP (1993)

pulse length	100 μsec
max power	750 kW
max efficiency	32% at P = 300 kW
gain	22 dB at P = 600 kW
instantaneous bandwidth at -3 dB	0.6 %

The bandwidth was limited by the Q-factor of the output cavity which was about 320.

High average power four-cavity W-band (94 GHz) gyroklystron developed jointly by NRL, the University of Maryland, the industrial companies Litton and CPI (1999)

Over 10 kW average power with 11% duty cycle (100 μsec pulse, 1.1 kHz repetition rate)

instantaneous bandwidth at the – 3 dB level	420 MHz (0,5%)
gain	35 dB
efficiency	33%

Institute of Applied Physics, Russian Academy of Sciences

GYRO – BACKWARD-WAVE OSCILLATOR

The gyro-BWO is based on the resonant cyclotron interaction of electrons gyrating in the external magnetic field with the electromagnetic field traveling in the direction of the longitudinal velocity of electrons. The gyro-BWO operating with a traveling wave of non-resonant microwave structure can provide a broad-band smooth frequency tuning by variation of the magnetic field strength or the electron beam energy.

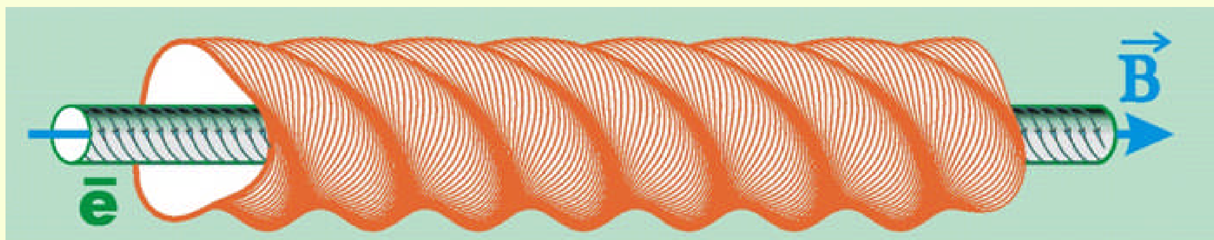
Short-pulse K_a-band gyro-BWO operating at the fundamental cyclotron harmonic and fundamental TE_{10} mode of a smooth cylindrical waveguide (1990 – 1993)

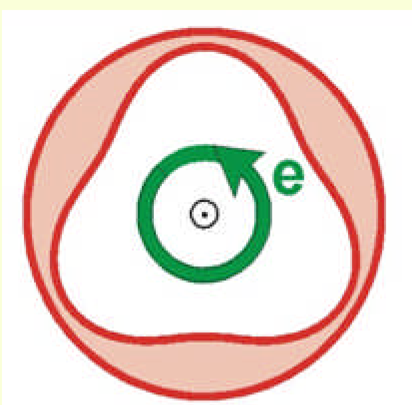
max power	7 kW
efficiency	20%
continuous magnetic filed tuning bandwidth	
(from 27.5 to 31.5 GHz)	13%
voltage tuning bandwidth	3% at a half-power level

The relatively low efficiency of backward-wave oscillators are explained by an unfavorable axial structure of the RF field. Electrons are modulated near the entrance to the waveguide structure by a large amplitude RF field while electron bunches lose the energy near the exit by the field of a small amplitude. However, the efficiency can be drastically increased up to 30 and even to 50% by the tapering of the external magnetic field or the waveguide radius.

GYRO-BWO with HELICALLY RIPPLED WAVEGUIDE

A proper chosen helical corrugation of the surface of an oversized circular waveguide provides dispersion of a circular polarised eigenmode favourable for the travelling-wave based gyro-devices, such as gyro-BWO and gyro-TWT. The main advantage of so produced eigenwave dispersion is in its sufficiently large group velocity at zero axial wavenumber, which ensures a broadband operation with minimum negative impact of the electron velocity spread





$$r(\varphi, z) = r_0 + l\cos\left[\frac{2\pi}{d} z - 3\varphi\right]$$

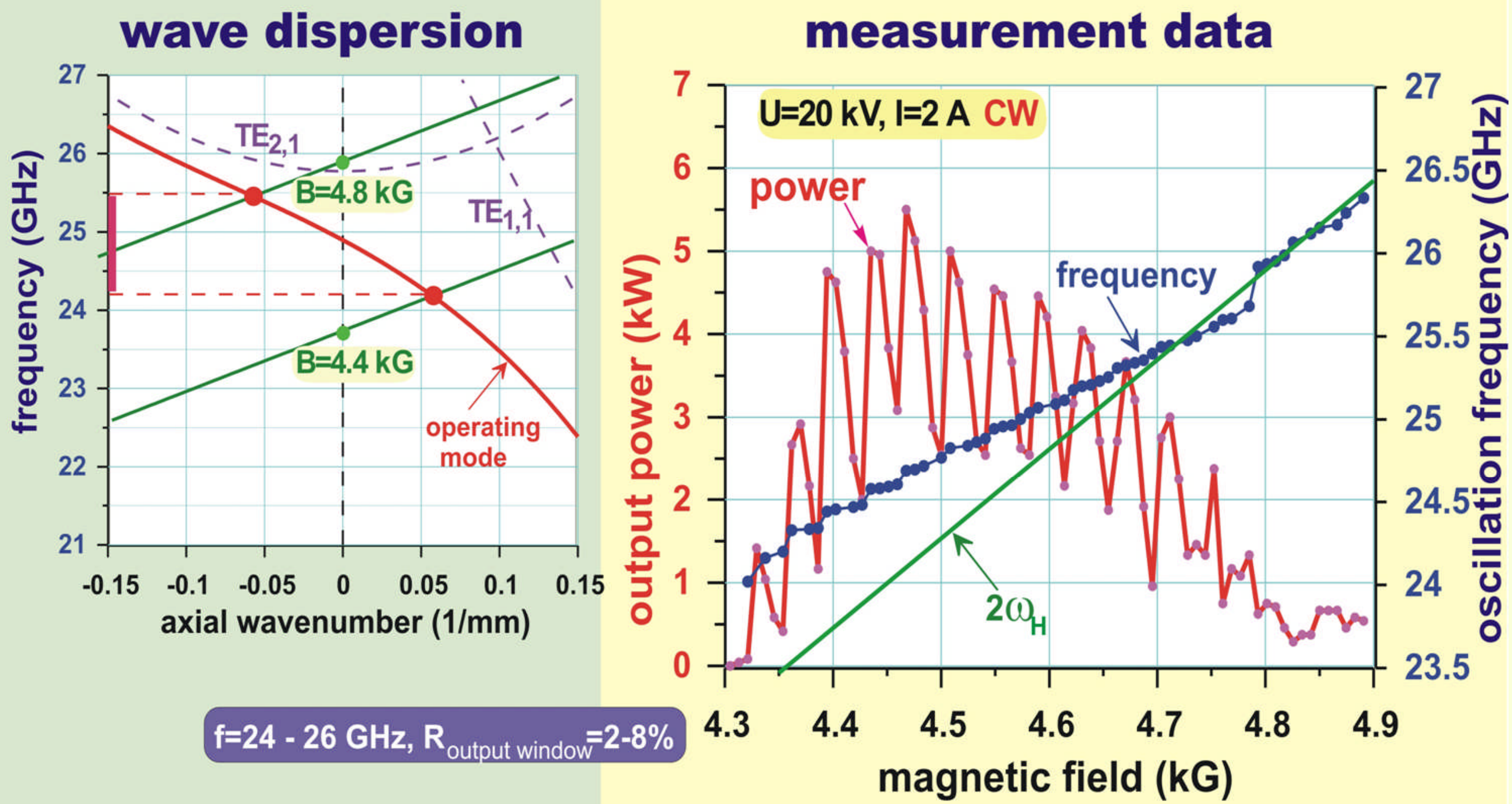
axis-encircling electron beam

operation mode – TE_{21} 

output mode – TE_{11} 

2^{nd} cyclotron harmonic interaction

Institute of Applied Physics, Russian Academy of Sciences



f=24 - 26 GHz, $R_{output\ window}$=2-8%

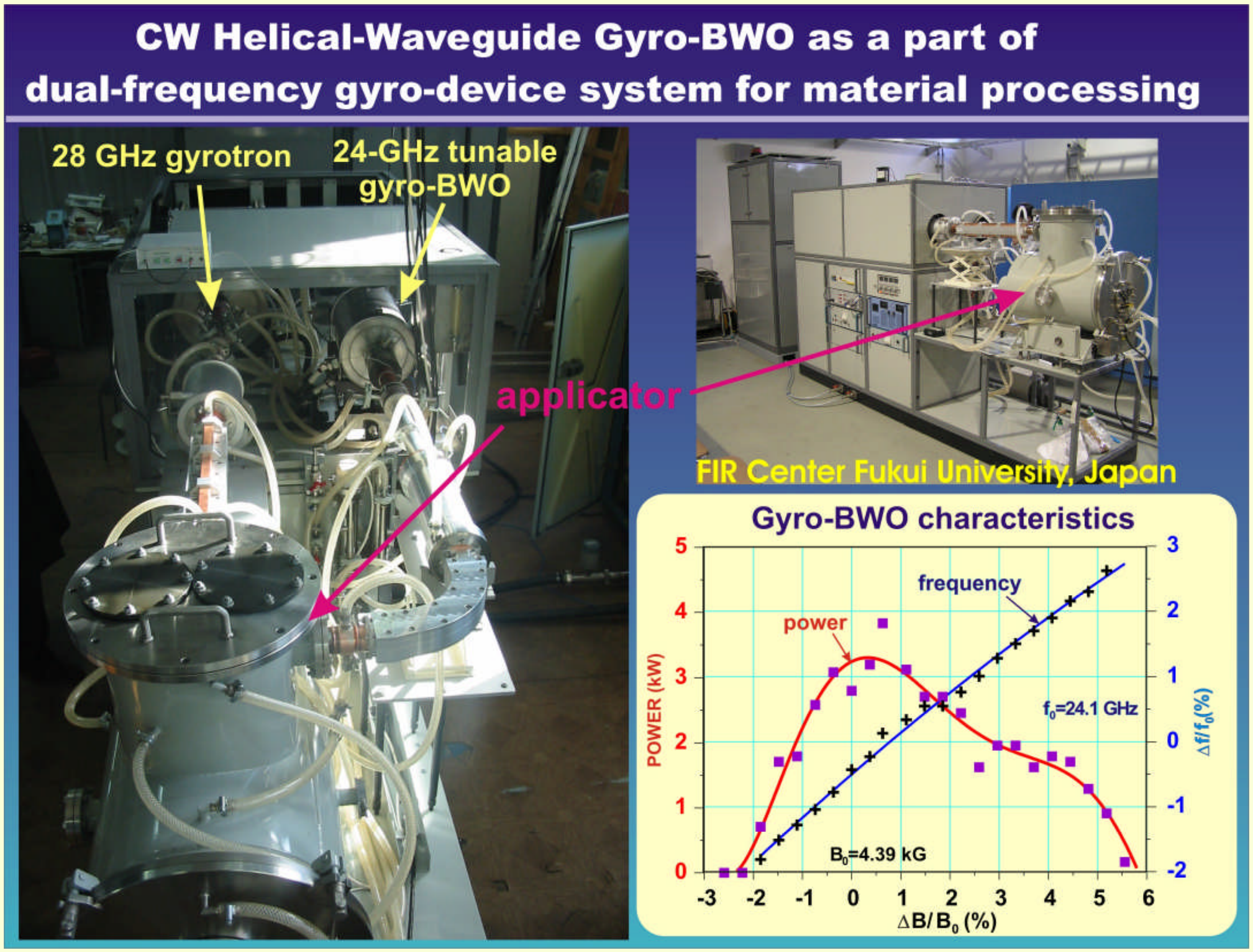
frequency tuning by voltage
U=20±4 kV f=24.65±0.1 GHz

frequency tuning band
$\Delta f_{1/2}$=1.2 GHz (≈ 5%)

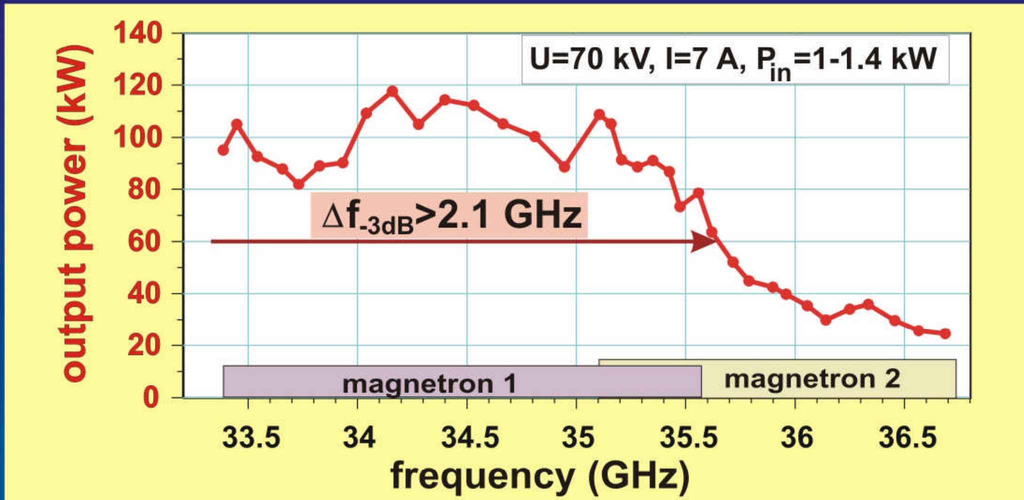
Institute of Applied Physics, Russian Academy of Sciences

TWO-FREQUENCY GYRO-DEVICE BASED SYSTEM

A 2.5 kW CW 24 GHz gyro-BWO of a similar design has been incorporated in a two-frequency gyro-device based system for microwave processing of materials, produced by IAP for the Far Infrared Center, Fukui University, Japan. Another microwave source in this system was a 15 kW CW 28 GHz gyrotron



Ka-band helical-waveguide gyro-TWT with high average power.



First experimental results (July 2007).

U=70 kV, I=6-8 A, P_{in}=1-1.4 kW

max P_{out}=100-130 kW

pulse length ≈ 100 μs, P.R.F.=10 Hz

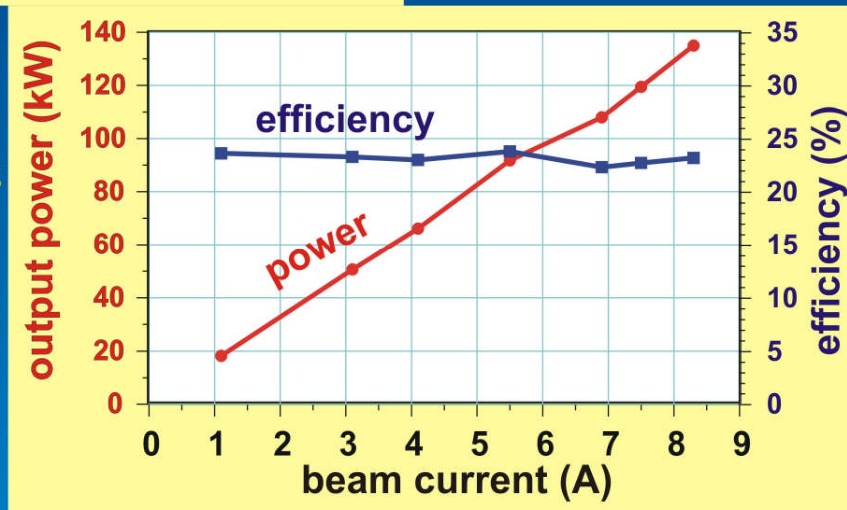
efficiency=22-24%

gain ≈ 20 dB

bandwidth>2.1 GHz (6%)

average power ≈ 100 W

limited by HV power supply and RF driving source



CONCLUSION

The experimental results achieved to date demonstrate that gyro-devices of all considered here types can meet the requirements of the next generation of ECRISs in terms of power and frequency. As for the requirements for a frequency bandwidth and frequency sweeping they can also be met but the detailed specification should be elaborated for each concrete facility in order to develop a gyro-device most precisely fitting a user’s needs. There is a trade-off between performance characteristics, and priorities are dictated by a given application.

It is clear, an increase in both a power and frequency of millimeter wave sources that feed the ECRISs requires the use of a new type of microwave transmission lines. The lines should be composed of the oversized multimode and/or quasioptical components. A large experience in the designing such components and transmission lines as whole acquired to date as the result of the development of millimeter wave power facilities for high power applications.

Frequency tuning in gyrotrons

The gyrotrons operate at near the electron cyclotron frequency

$$\omega_c = eH_0/\gamma m_0$$

$$\gamma = 1 + eU/m_0c^2$$

e is the electric charge, m_0 is the mass of the electron

Operating frequency $\omega \approx \omega_c$ can be controlled only by varying the electron beam energy eU (rapid electrical tuning) or the static magnetic field strength H_0 (slow magnetic tuning).

Frequency bandwidth

$\Delta\omega = (\omega/Q)\bullet F(I_{beam}, U_{beam}, H_0, \ldots)$, where Q is the quality-factor

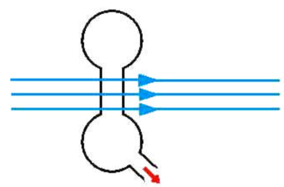
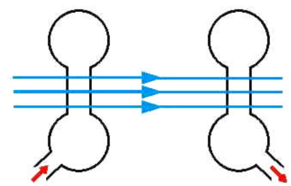
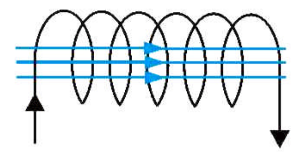
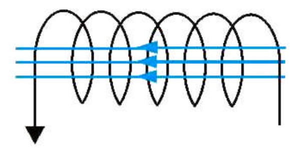
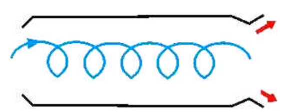
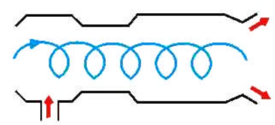
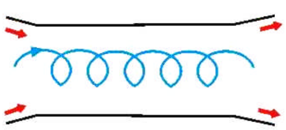
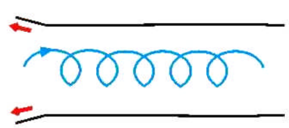
Typically, $Q \geq 10^3$ and $Q >> \Delta F/\Delta x$

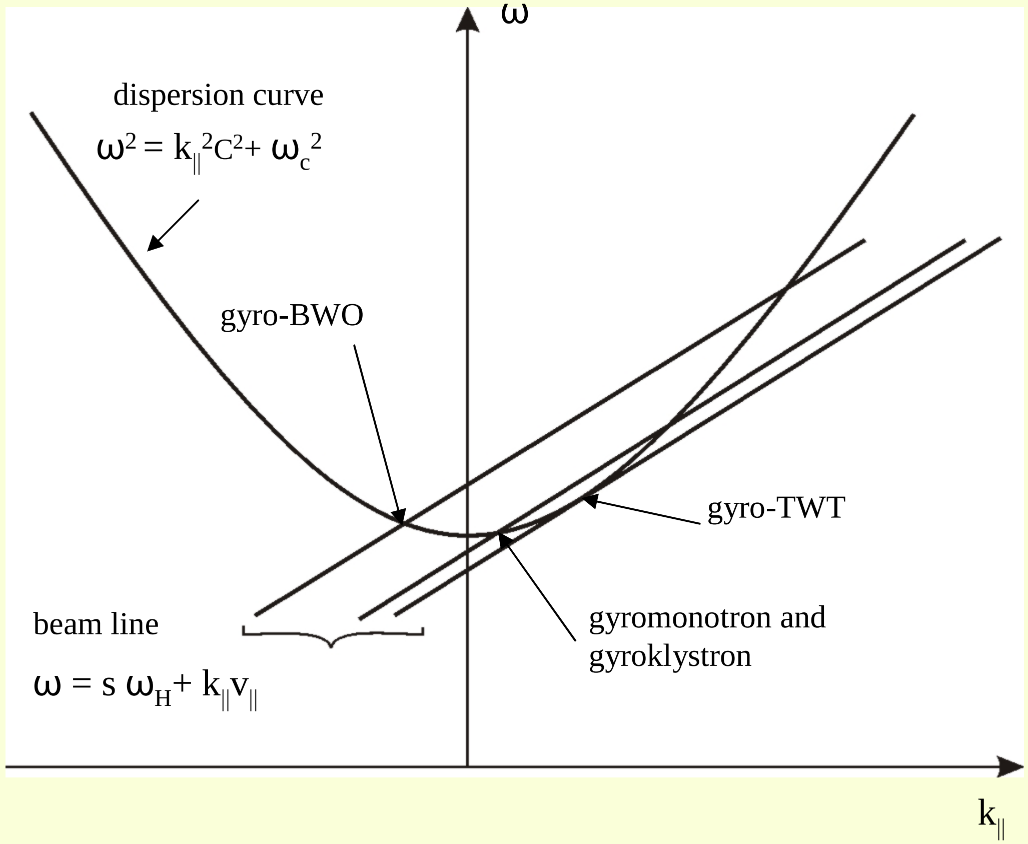
$(\Delta\omega/\omega)_{half\ power} \leq$ 10^{-3} at H_0 - variation

$5 \cdot 10^{-4}$ at variation of U_a (in triode electron gun)

10^{-4} at variation of U_{beam}

Formally, the orbital bunching of gyrating relativistic electrons has much in common with bunching of linear electron beams being used in ordinary “O” type devices. Therefore each CRM has its “O” type analog: monotron, klystron, traveling-wave-tube (TWT), backward-wave oscillator (BWO).

“O” type device	 Monotron	 Klystron	 TWT	 BWO
Type of gyro	 Gyrotron	 Gyroklystron	 Gyro-TWT	 Gyro-BWO



Dispersion diagram showing the operating point for gyro-devices:

ω_H – electron cyclotron frequency,

ω_c – the cutoff frequency of the waveguide mode,

$k_{||}$ – axial wave number,

$v_{||}$ – axial velocity of electron beam

s – number of harmonic