Tendencies in the Development of High-Power Gyrotrons

G.G.Denisov

Institute of Applied Physics
Russian Academy of Sciences

GYCOM Ltd.

Nizhny Novgorod, Russia

JAERI/TOSHIBA IAP/GYCOM FZK/THALES CPI/GA

Gyro-devices

Extraordinary high average power at millimeter wavelengths

MW power level in oscillators; tens kW in amplifiers

Main applications:

- **ECW systems for plasma fusion installations (70-170GHz/1MW)**
- Technological applications (ceramics sintering, … 24-80 GHz/3-30kW)
- Plasma physics and plasma chemistry

Discussions and studies

• Radar systems	amp., 35; 94 GHz / 10kW
• Spectroscopy	tunability
• **Future linear accelerators**	**amp. 30 GHz / >10 MW/1mks**
• Medicine	submm. 1-100 W
•………..	

OUTLINE OF THE TALK

- **Gyrotrons for fusion**
- **GK for radars**
- **Multi MW GK**

ECW systems (examples)

Running installations:

DIII-D *3×0.8MW/110GHz/2sec + 3×0.6MW/110 GHz/10 sec*

TCV *6×0.5MW/82.6GHz/2sec + 3×0.4 /118 GHz/ 5* sec*

JT-60U *4 x 1 MW/110 GHz/5sec*

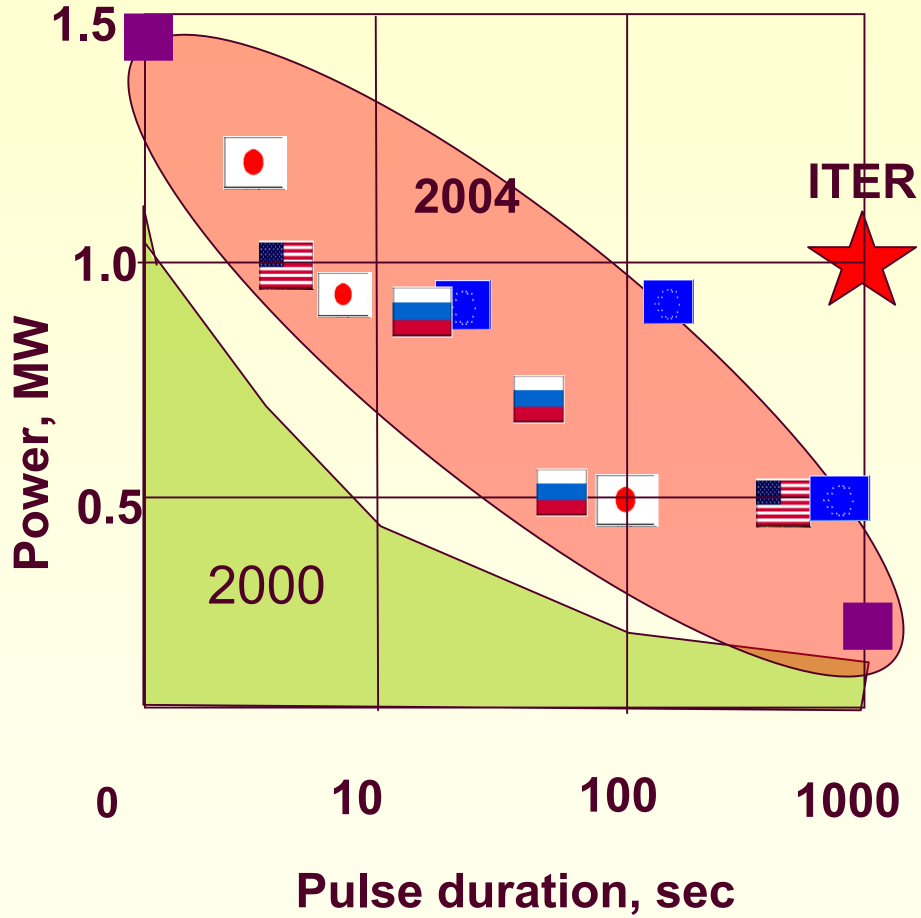
LHD, ASDEX-Up, T-10, W7-AS, Triam…

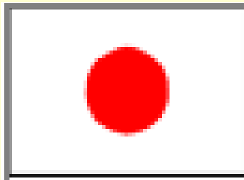
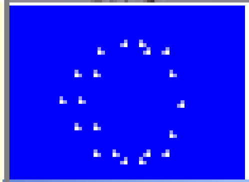
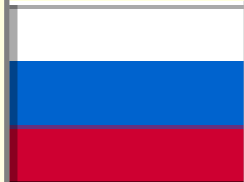
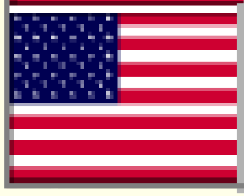
Future installations:

- **ITER** **24**× *1MW/170GHz/CW*
- W7-X *10× 1MW/140GHz/CW*

IAP
GYCOM

Gyrotron performance. Main results since 2000.



	170 GHz, 0.9 MW, 9 sec 0.5MW, 100 sec 110 GHz, 1.2 MW, 4 sec
	140 GHz, 0.9 MW, 180 сек 0.5 MW, 900 сек
	170 GHz, 0.5 MW, 80 sec 0.85 MW, 19 sec 140 GHz 0.8 MW, 10 sec
	110 GHz, 1.0 MW, 5 сек 140 GHz, 0.5MW, 700 sec

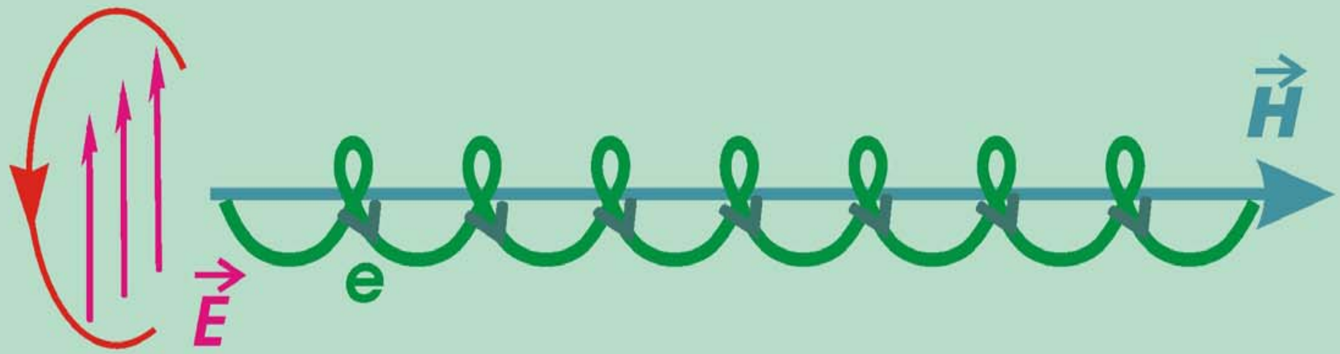
Efficiency 40-50%

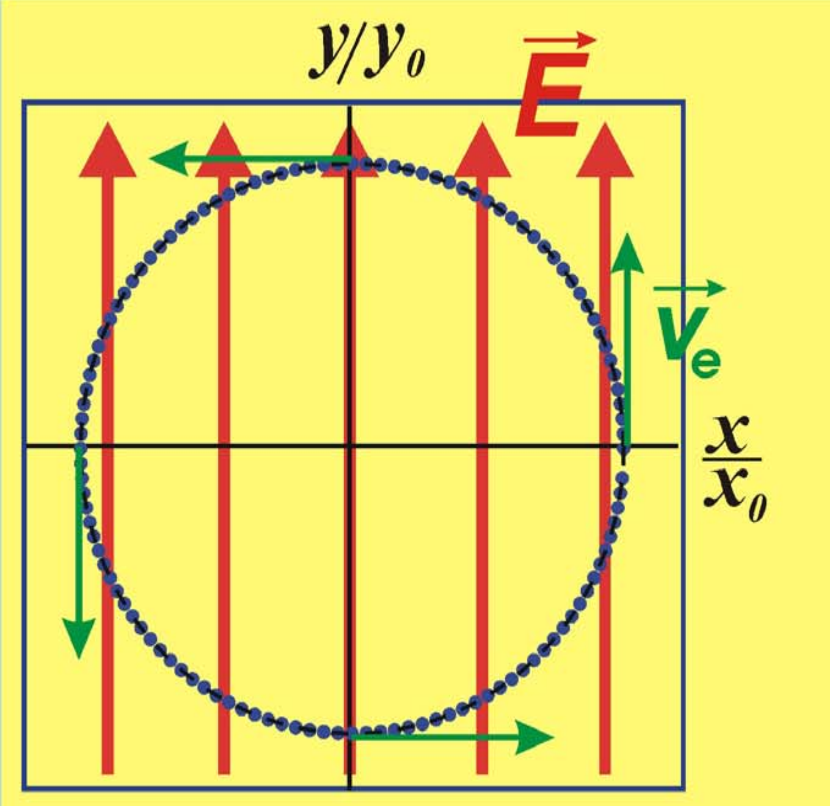
Why gyrotron is so powerful and efficient?

Gyrotron based on:

- *Emission of radiation by electrons rotating in magnetic field. Rotation phase bunching due to dependence of cyclotron frequency on electron energy.*
- *Cylindrical quasi-optical cavity – high-order operating modes. XX-large cavity and e-beam sizes*
- *Nonlinear electron-wave interaction. Mode competition*
- *Efficient conversion of the operating mode into a paraxial wave beam*

Cyclotron Masers





$$\omega \approx \omega_H + k_{\parallel} v_{\parallel}$$

$$\mathcal{E} = mc^2\gamma \qquad \omega_H = \frac{eH}{mc\gamma}$$

Inertial bunching

$$\begin{cases} \dfrac{d\Theta}{dt} = \omega_H \\ \dfrac{d\mathcal{E}}{dt} = -e(\vec{V}\vec{E}) \end{cases}$$

$$V_x + iV_y = iV_{\perp} e^{i\Theta}$$

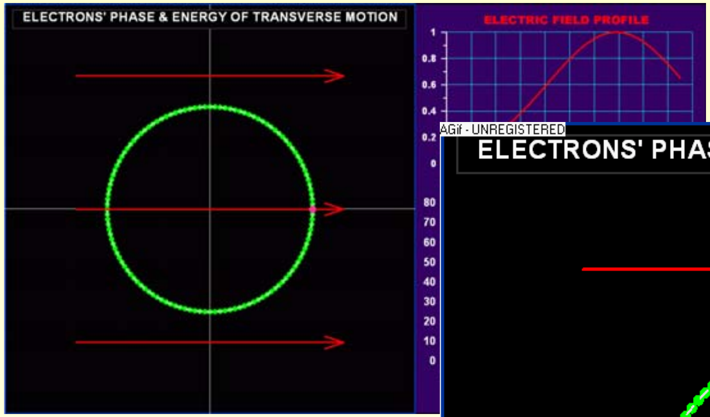
$$E_x + iE_y = iE_0 e^{i\omega t}$$

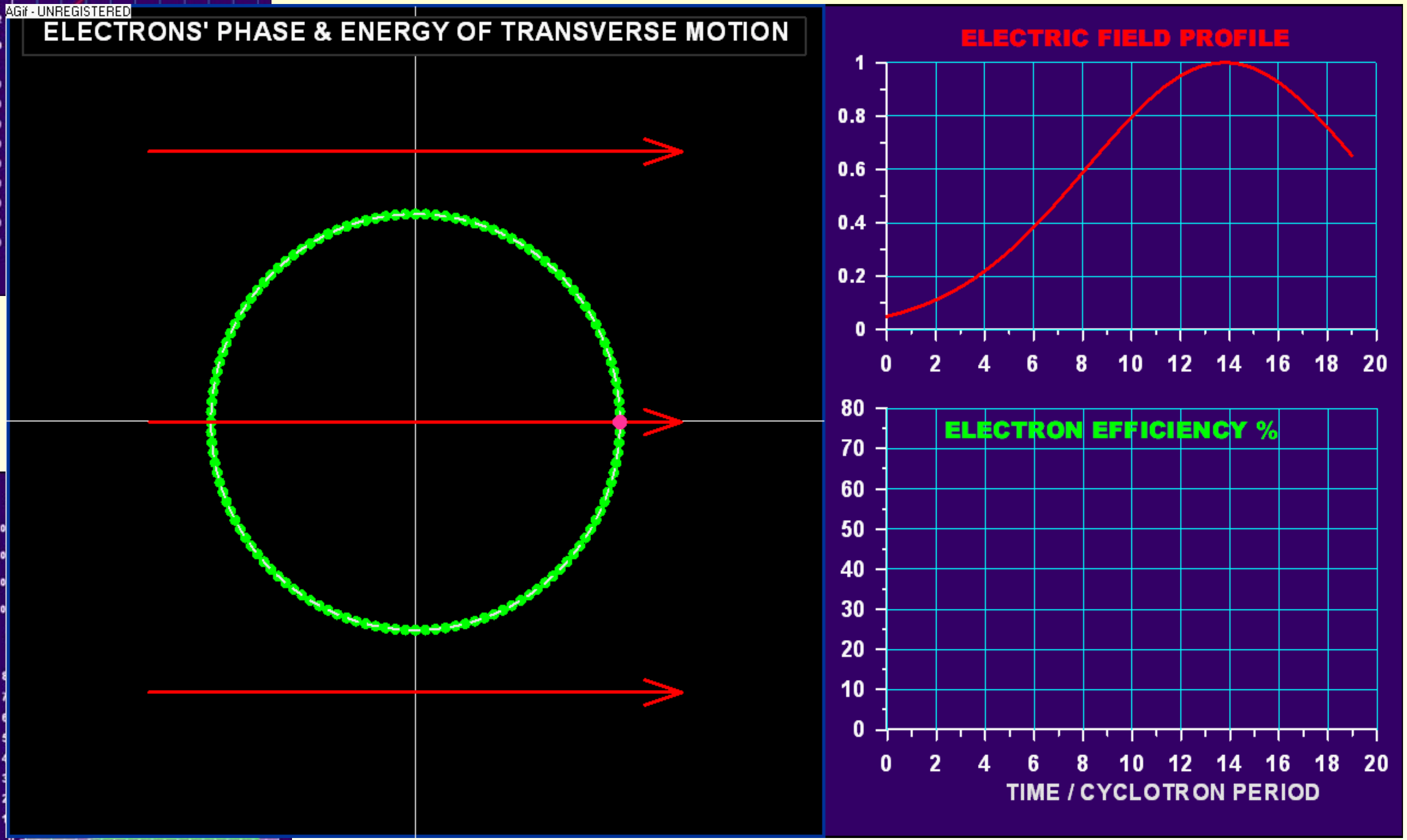
$$x + iy = \frac{V_{\perp}}{\omega_H} e^{i\Theta}$$

IAP
GYCOM

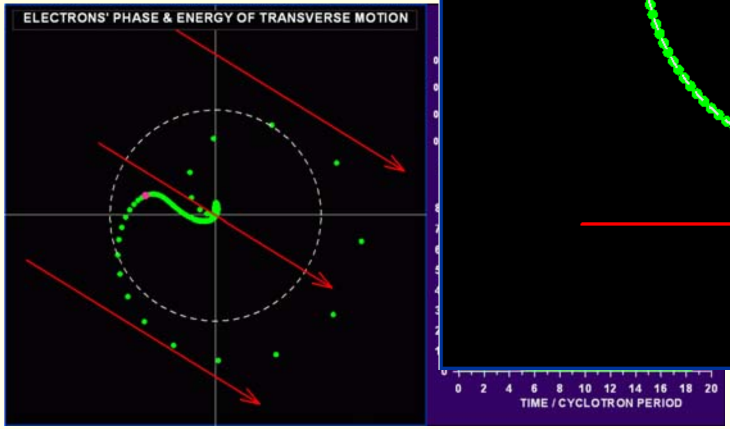
Cavity entrance

Phase bunching (optimal field profile)





Cavity exit



During last 10 years principal steps were made in development of MW /CW gyrotrons:

- Efficient gyrotron operation was demonstrated at very high volume cavity modes. This solves the problem of thermal loading of the cavity walls. Very efficient QO converters with low diffraction losses inside the tube were developed.

- Advanced gyrotrons were equipped with depressed collectors providing energy recovery from the worked-out e- beam. Typical gyrotron efficiency is now about 50%.

- Gyrotron windows based on CVD diamond disks with a very low absorption and very high heat conductivity were developed.

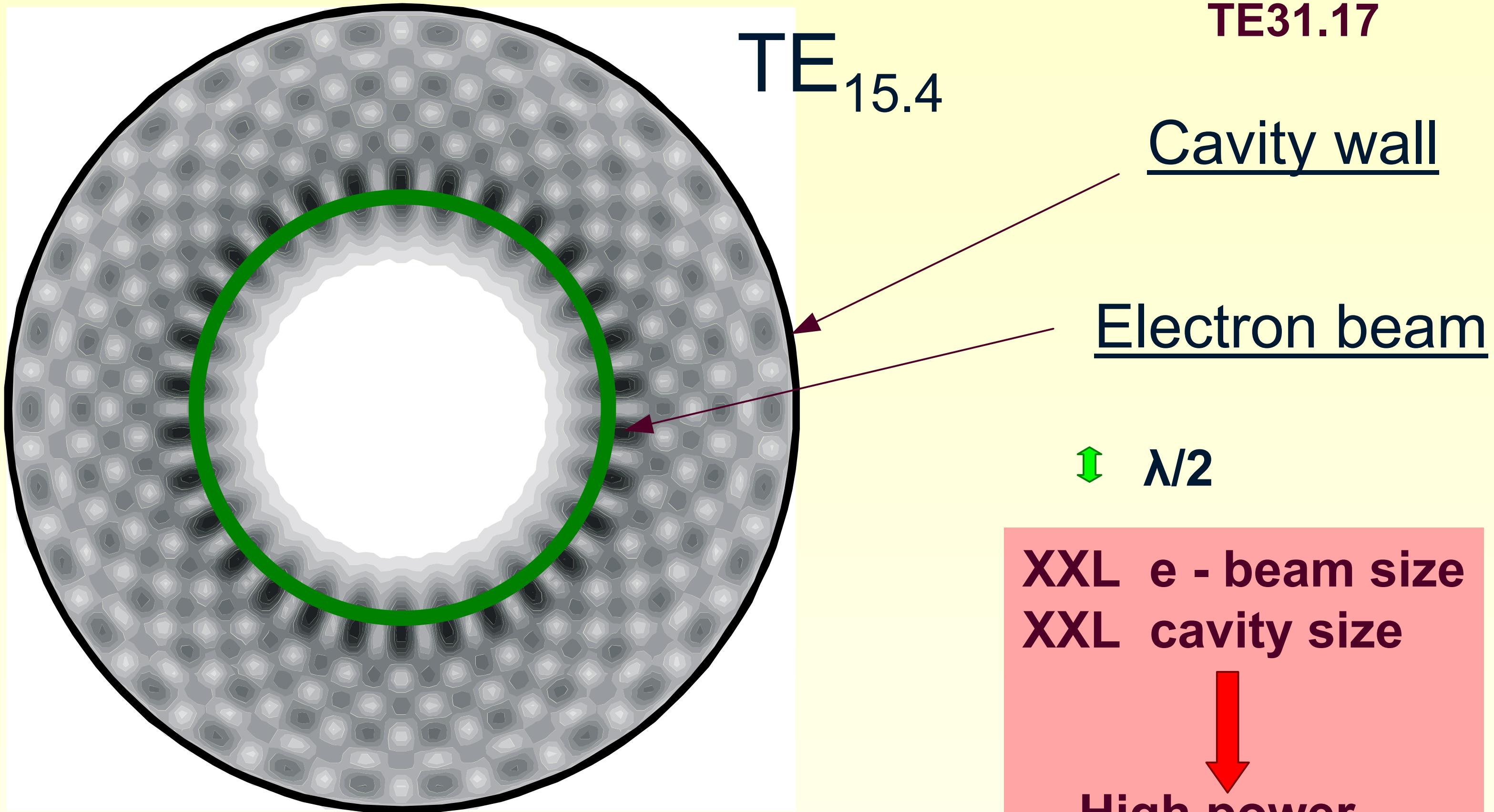
- These years gave experience of testing and use of megawatt power level gyrotrons. Important auxiliaries and measurement methods were developed.

- Principal solutions for 1 MW power gyrotron have been found. This point allows one to make prospects for more advanced gyrotrons.
  Developments of multi-megawatt gyrotrons and gyrotrons with frequency tunability are in progress.

High–order operating mode

IAP
GYCOM

TE25.10
TE31.17

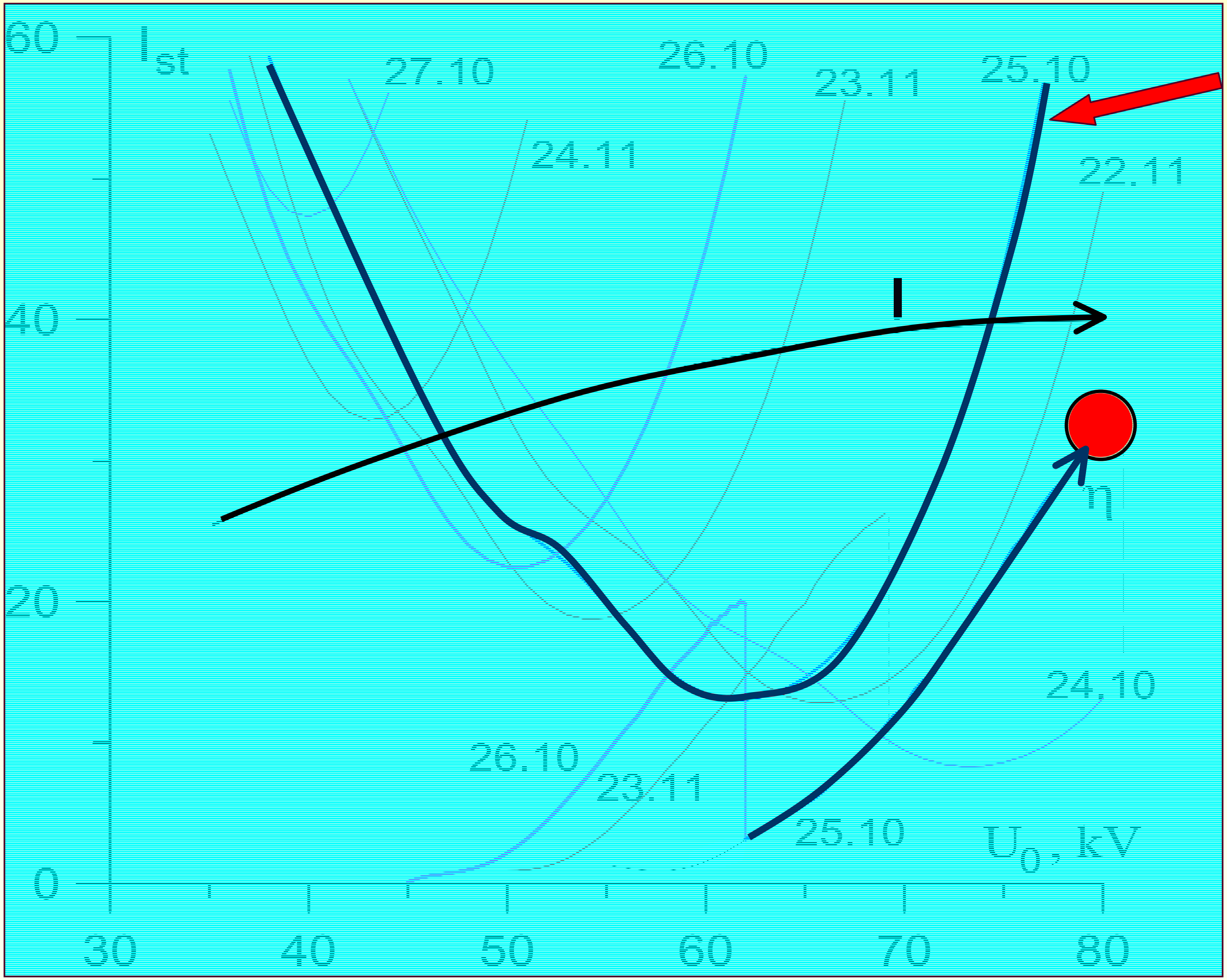


XXL e - beam size
XXL cavity size
High power

The specific power is limited for gyrotron cavity configuration as
$$\Delta P/\Delta S < \Delta P/\Delta S)_{crit} = 2\text{-}3\ kW/cm^2$$
and power enhancement is linked with cavity size increase.

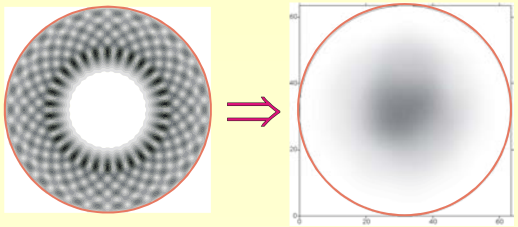
Scenario of operating mode ($TE_{25.10}$) switching on

Eff.,%
I, A



IAP
GYCOM

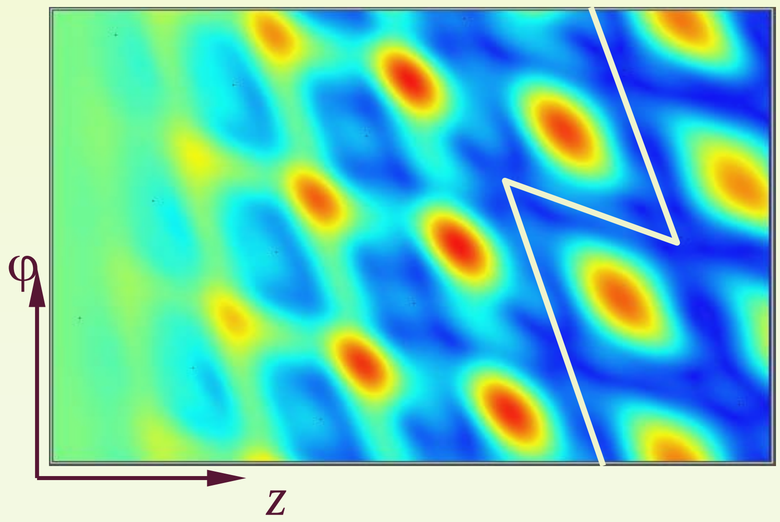
Conversion of high-order modes



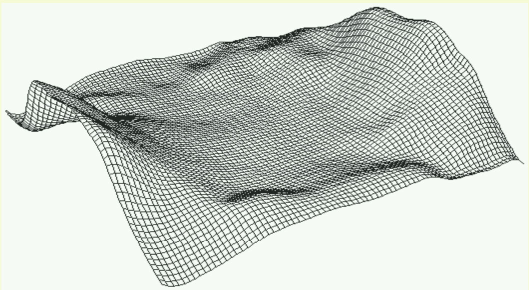
High-order modes (radial index p >> 1) → Gaussian wave beam

95-98%

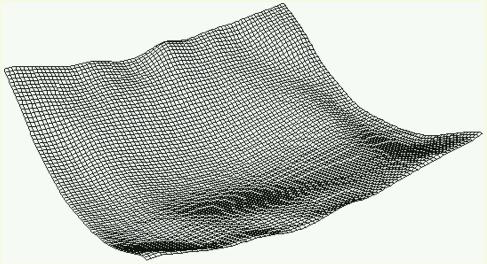
Field intensity on the wall of pre-shaping waveguide section



Shaped mirrors for gyrotrons



Зеркало №1: 160×170×2.2 мм



Зеркало №2: 80×85×0.97 мм

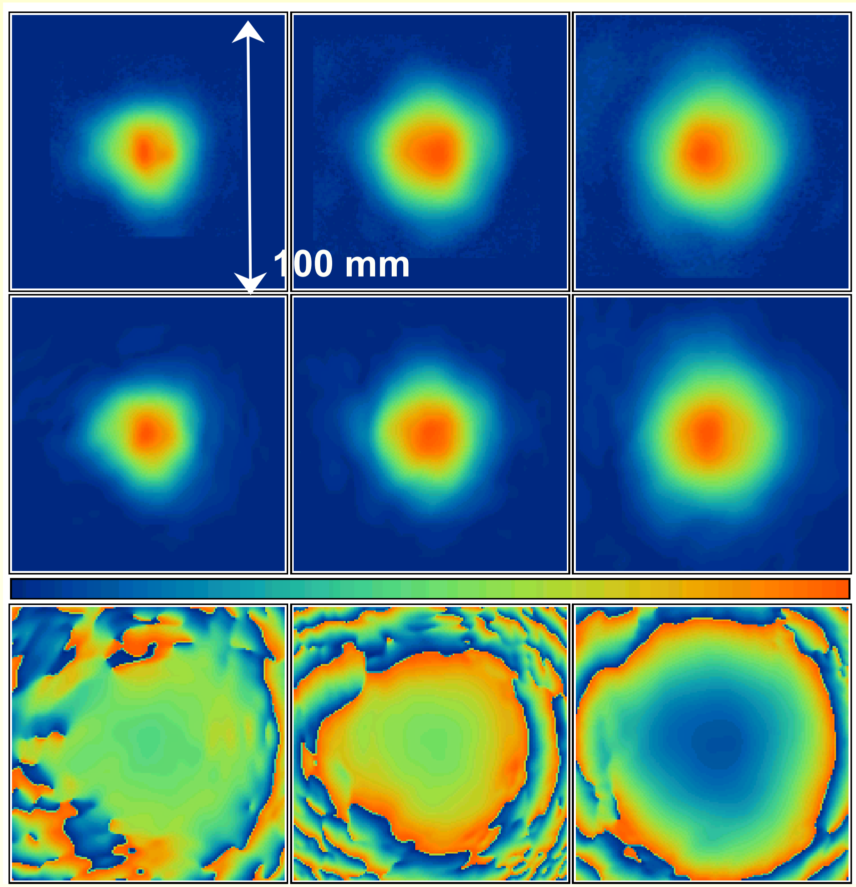
IAP
GYCOM

Measurement of amplitude and phase structures of output wave beam. 1MW/140GHz/10 sec gyrotron

$\eta^{1,2}_{coup}$ → 99.49% 99.39% 99.49%

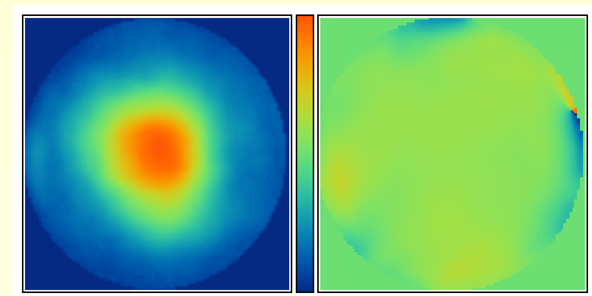
Measurement (1)

Theory (2)



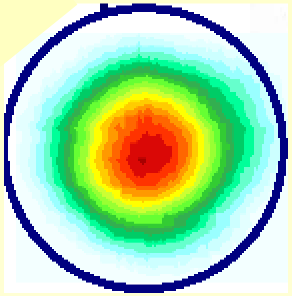
Z → 310mm 560mm 810mm

Amplitude Phase

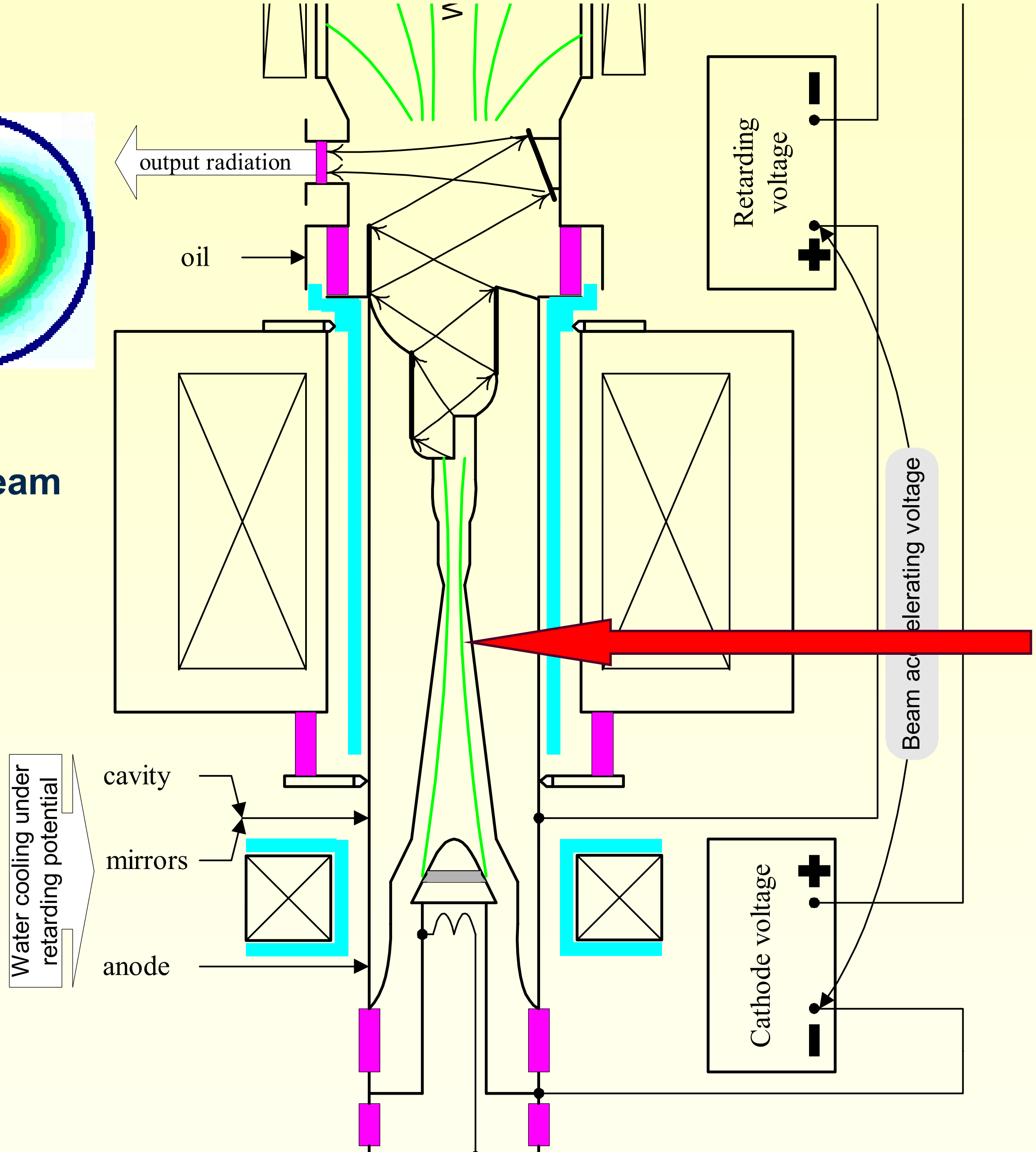


Gyrotron output flange

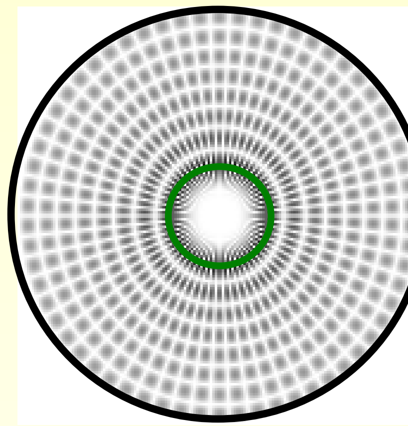
$\eta_{gauss} = 97.4\%$



Output wave beam



Operating mode



$TE_{31.8}$, $TE_{25.10}$
Ø ≈ 20 λ

Depressed collectors in MW gyrotrons

Advantages:

- great reduction of power dissipated on a collector
  (*η = 33% → 2MW on the collector; η = 50% → 1MW)*

  Water flow and collector size ↓
  X-rays level

- simplifications in power supply / possibility to operate at higher electron energies

  → lower current (better e-beam quality)

  → frequency tuning by voltage

IAP
GYCOM

CVD diamond windows for gyrotrons

Different window concepts were under analysis last 10 years:

- **Double-disk window**
- **Sapphire cryo-window**
- **Distributed and multi-beam window**
- **Silicon window**
- ………………………
- **CVD diamond window**

A diamond disc has the following outstanding combination of features:

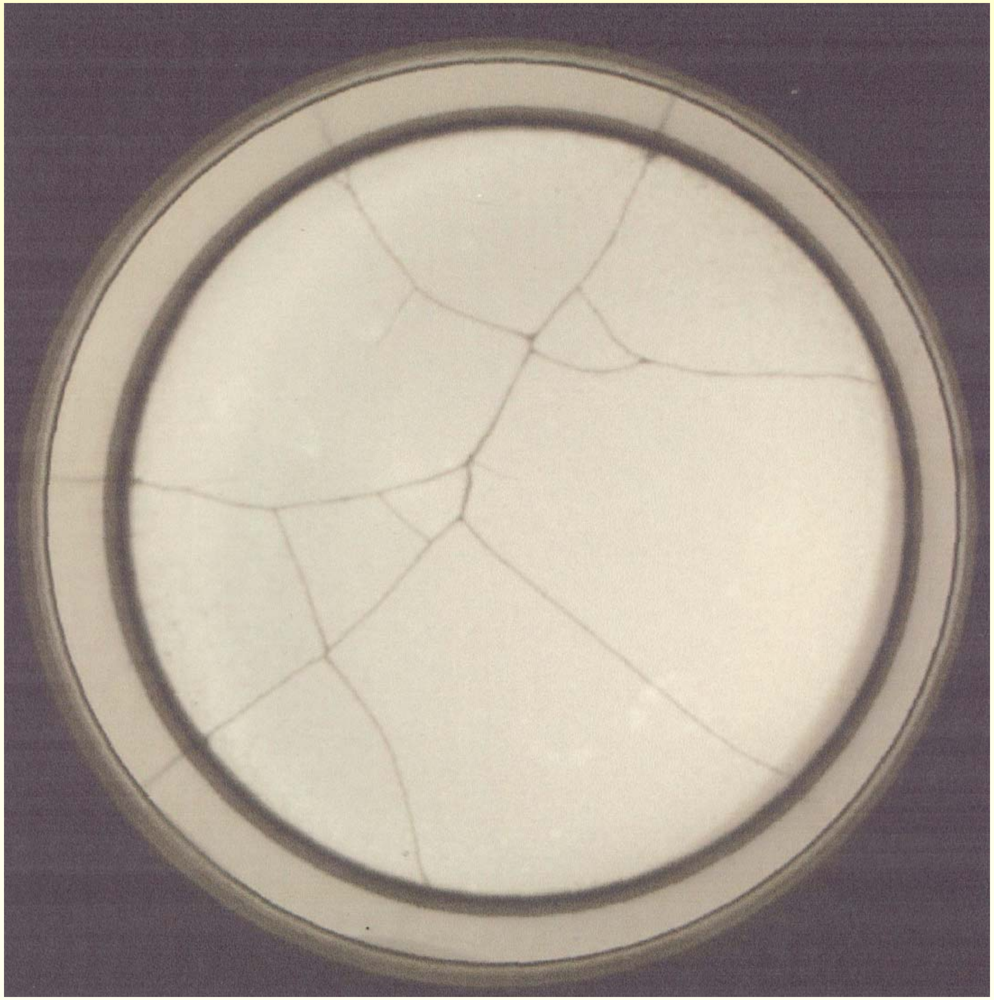
- **thermal conductivity** of the CVD diamond discs is close to the conductivity of natural diamonds (about four times higher than for copper) for very wide temperature range
- **low losses of microwaves** (loss tangent less than 10^{-5} at millimeter waves was demonstrated for many discs)
- **high mechanical properties** (disc of 1.5 mm thickness and 100 mm diameter can withstand several bars of gas pressure)

Diamond window mounted in 170 GHz ITER gyrotron

Photos of brazed diamond discs

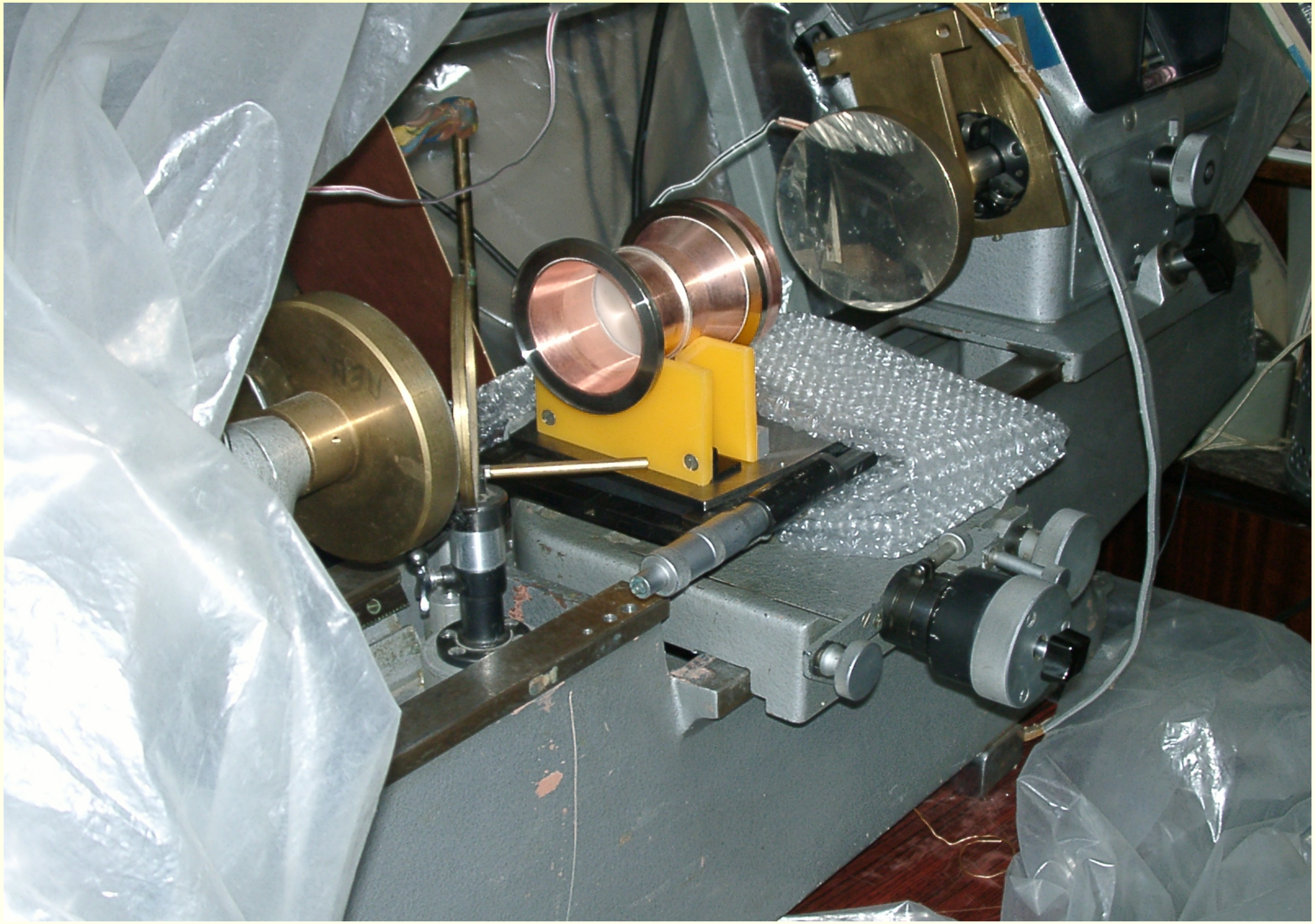
Before mounting

After the failure

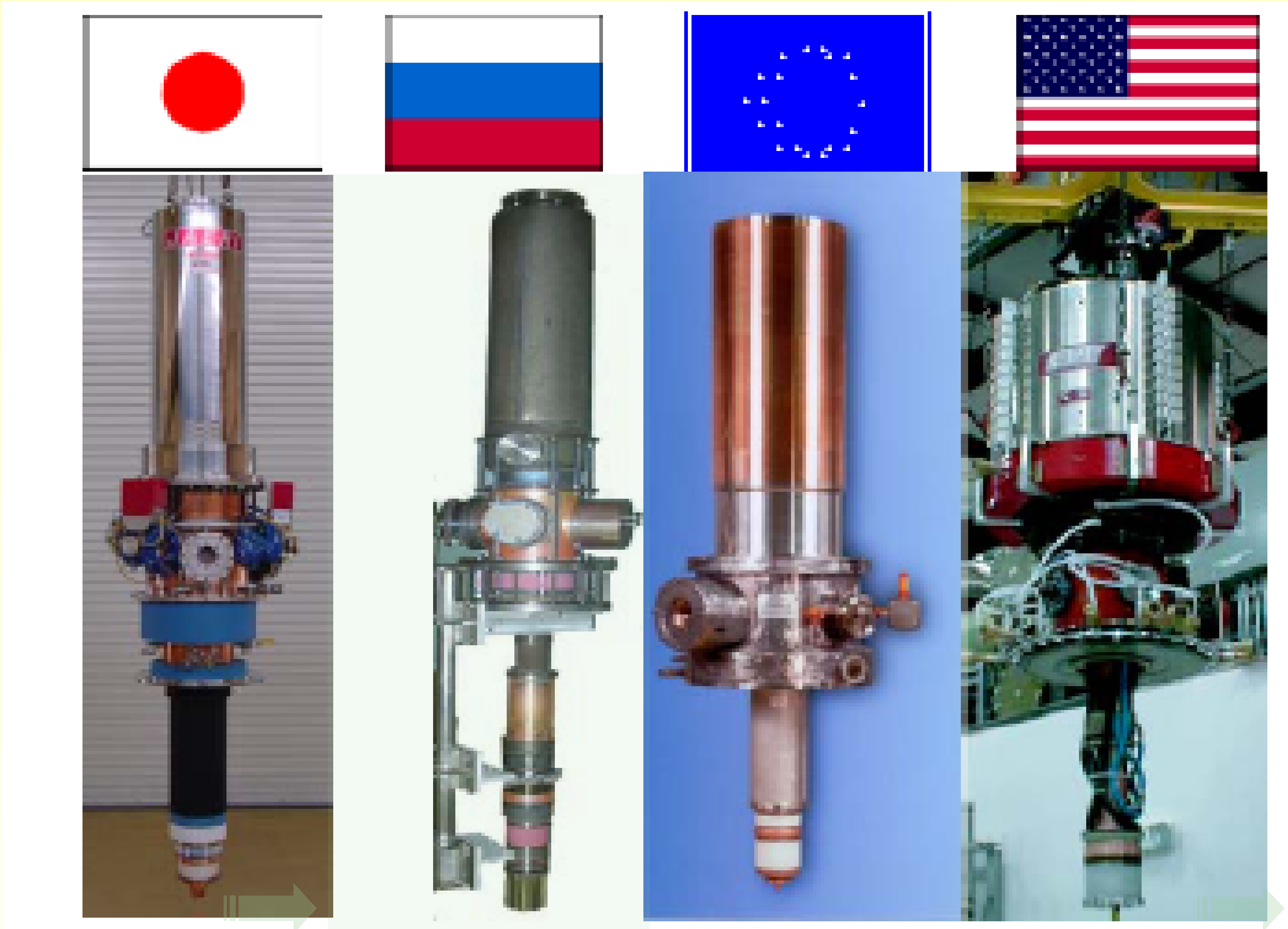


Setup for diamond disk production at IAP/GYCOM

High-temperature brazed disc (Gycom) in measurement setup



IAP
GYCOM



JAERI/TOSHIBA IAP/GYCOM FZK/THALES CPI/GA

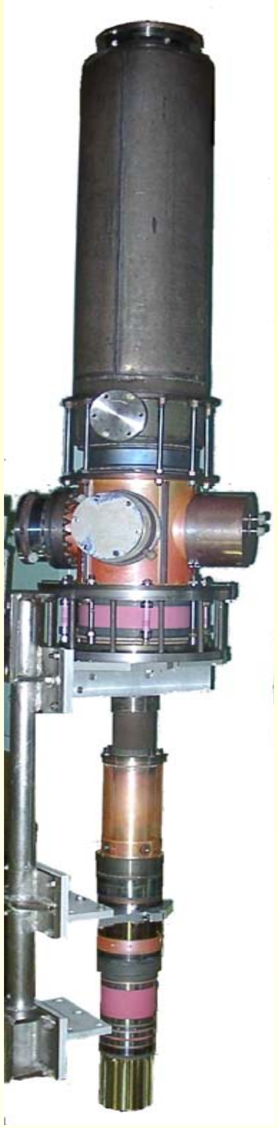
170-GHz GYROTRON (GYCOM, Russia)

All inner surfaces

are fabricated of copper and have adequate water cooling for CW operation.

Retarding voltage insulator ∅ 220mm

- is provided by flexible cuffs for welding and outside ceramic supports to remove mechanical stress;
- is protected by inner shield to prevent ceramic overheating due to scattered RF rays.



2003

0.5MW/ 80sec; 0.7 MW/40 sec; 0.85MW/19sec
45% efficiency

Future developments

- Achievement of true CW 1MW gyrotron operation
  (e.g. 10/100 sec $\rightarrow$ 1000 sec)
- Frequency tuning in 1 MW gyrotrons
  (2-3% step tuning, 10 frequencies)
- Development of 1.5 - 2 MW/CW gyrotron
  (some people want more)

Gyro-Klystrons

GK for radars

Multi MW GK

A Ka-BAND SECOND HARMONIC GYROKLYSTRON WITH PERMANENT MAGNET

Gyro-klystron amplifiers are of interest for millimeter-wave radar due to their capability to provide high peak and average power in the atmospheric propagation windows near 35 and 94 GHz. A Ka-band gyro-klystron operating at the fundamental harmonics requires an axial magnetic field of about 1.4 T provided usually by a superconducting coil.

Gyro-klystrons on the base of superconducting magnets:
35 GHz /0.7MW /40 kW /300MHz /25dB
94 GHz /0.2MW /5kW / 500 MHz / 22dB

The use of a superconducting magnet in radar is accompanied by some technical problems. Therefore, there is an interest in second harmonic gyro-klystron with a permanent magnet. Over last years an essential progress was attained in the development of Nd-Fe-B magnets capable to produce field strength up to 1T in a large volume.

Since that, during 1998-2002 IAP efforts were concentrated on the development and testing of a Ka-band second harmonic gyroklystron operating with PMS.

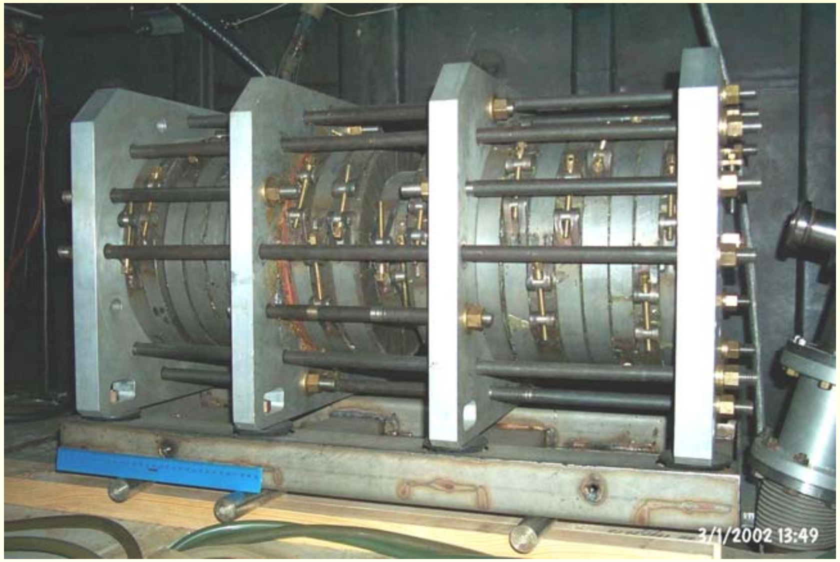
(Zasypkin et al)

Permanent Magnet System Design

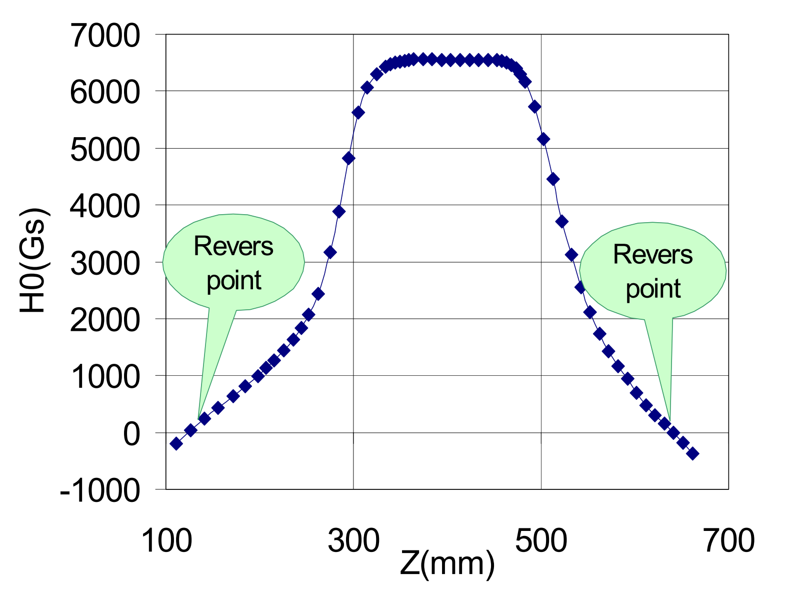
The PMS dimensions were simulated to satisfy the following requirements:

- axial magnetic field strength in the rf circuit should be 0.7 T
- flat top region length should be 140 mm with uniformity of 0.5%
- field gradient at the cathode emitter should not be larger than 150 Gauss/cm

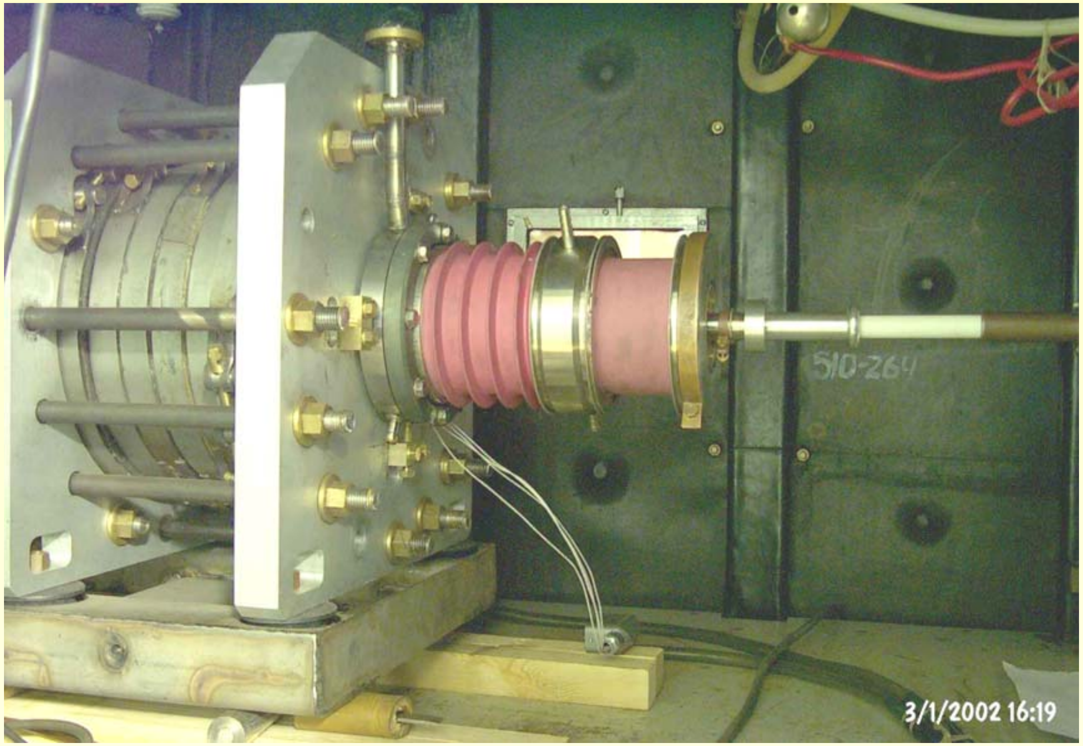
The bore diameter varies from 60 mm to 130 mm. The PMS total length is of 87 cm. The overall weight of the magnet system (including its rigging) is about 370 kg.



Permanent Magnet System



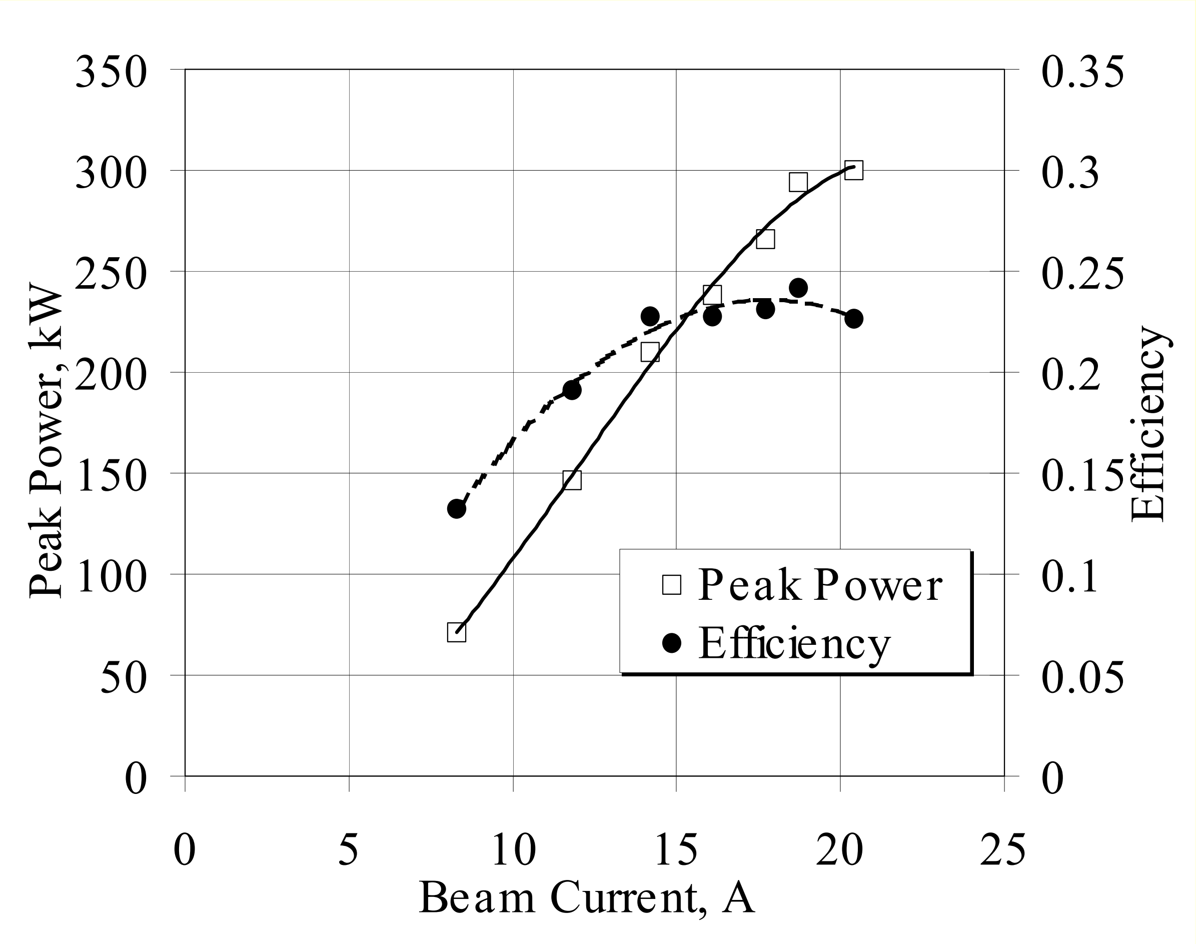
Magnetic Field Profile



GK prototype
in PMS

Pulse width 100 μsec
Pulse repetition - 5 Hz.

The measured full width half maximum (FWHM) bandwidth was 45 MHz



Peak Power and Efficiency vs Beam Current for Three-cavity Gyro-klystron With permanent magnet (U = 65kV).

K_a band ~10 MW gyro-devices:

an experiment and a project

E. Ilyakov*, I. Kulagin*, S. Kuzikov*, V. Lygin*, M. Moiseev*, M. Petelin*, N. Zaitsev*

PROBLEM ADDRESSED:

multi-megawatt pulse amplifiers for future electron-positron super-colliders

X-band :

0.5 MV/ 75 MW PPM klystron

Higher frequencies:

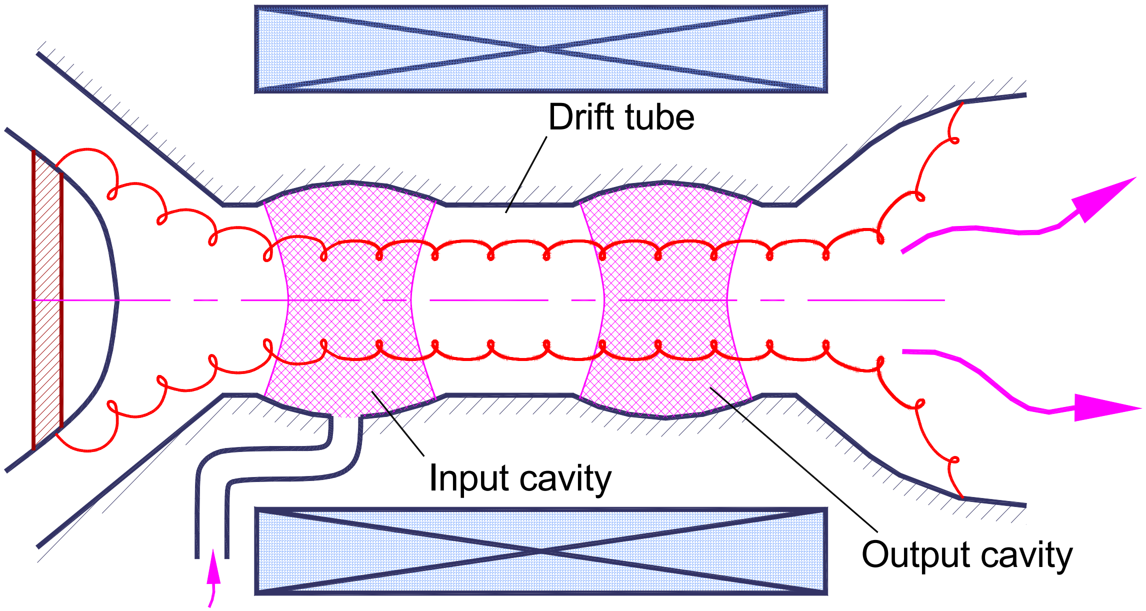
ubitron (free electron maser),

magnicon,

gyroklystron.

IAP
GYCOM

GYROKLYSTRON

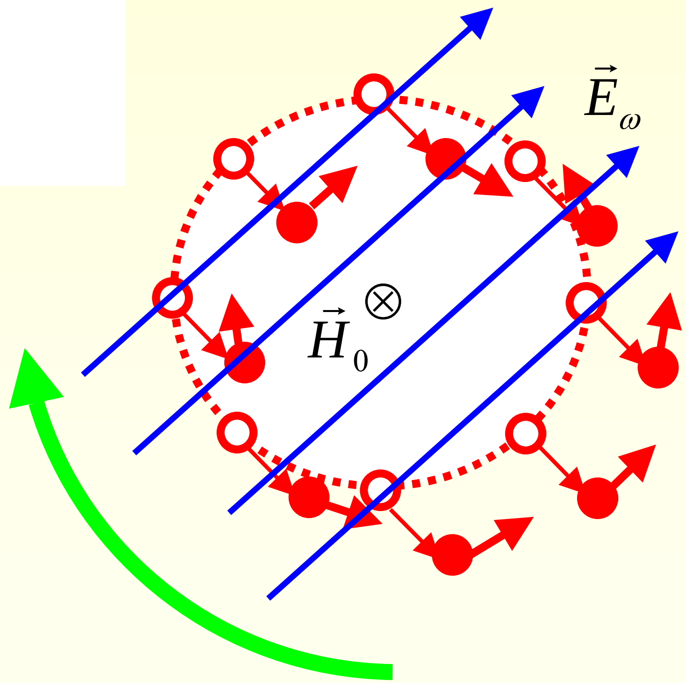


$$\omega = n\omega_H \qquad n = 1,2...$$

$$\omega_H = \frac{eH_0c}{E}$$

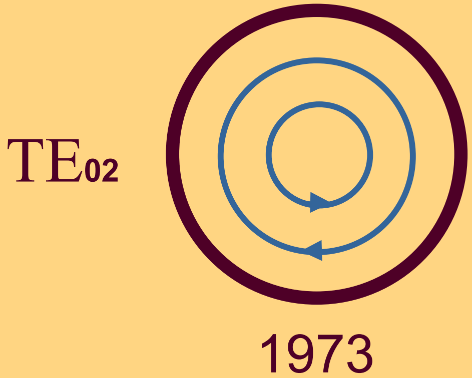
$$E = Mc^2$$

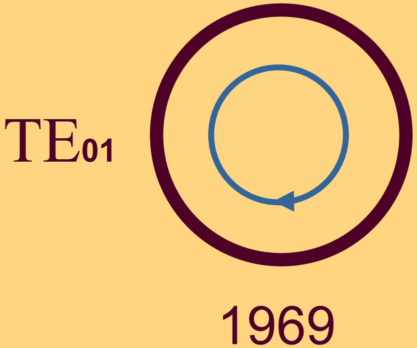
$$M = \frac{m}{\sqrt{1 - v^2/c^2}}$$



Azimuthal bunching is due to ***relativistic*** dependence of gyrofrequency on electron energy

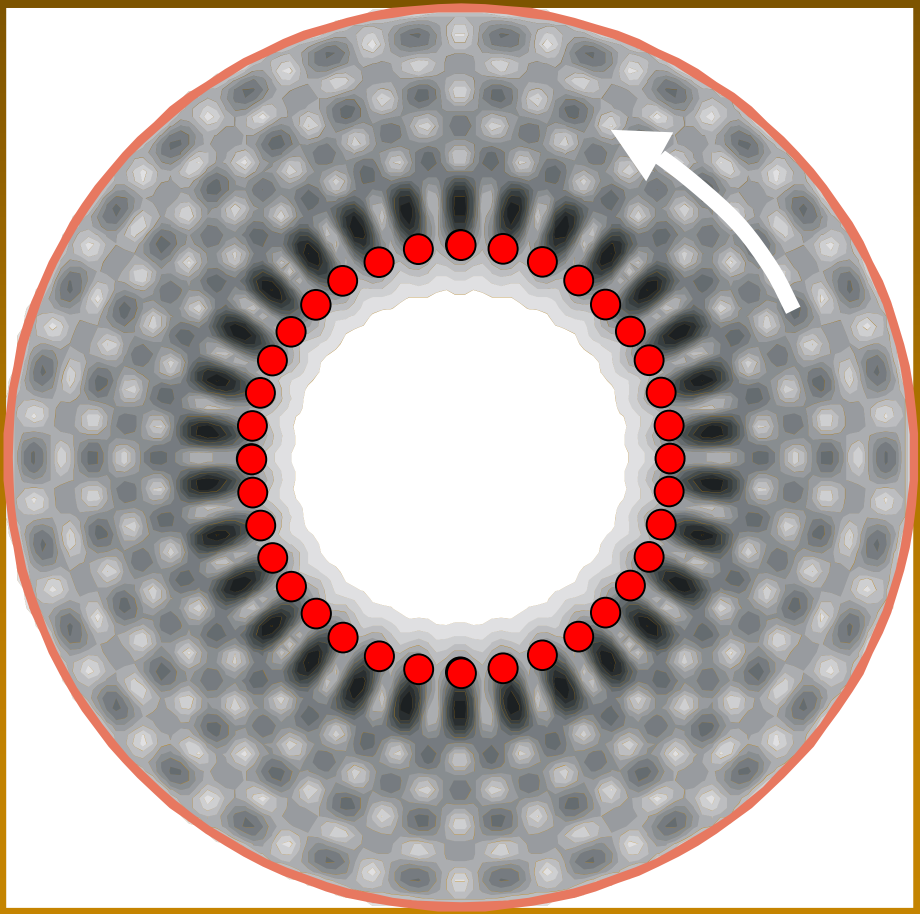
Gyroklystron modes





Mode with inner caustic close to tubular electron beam

- wins competition with rival modes,
- has relatively low field at the cavity wall.

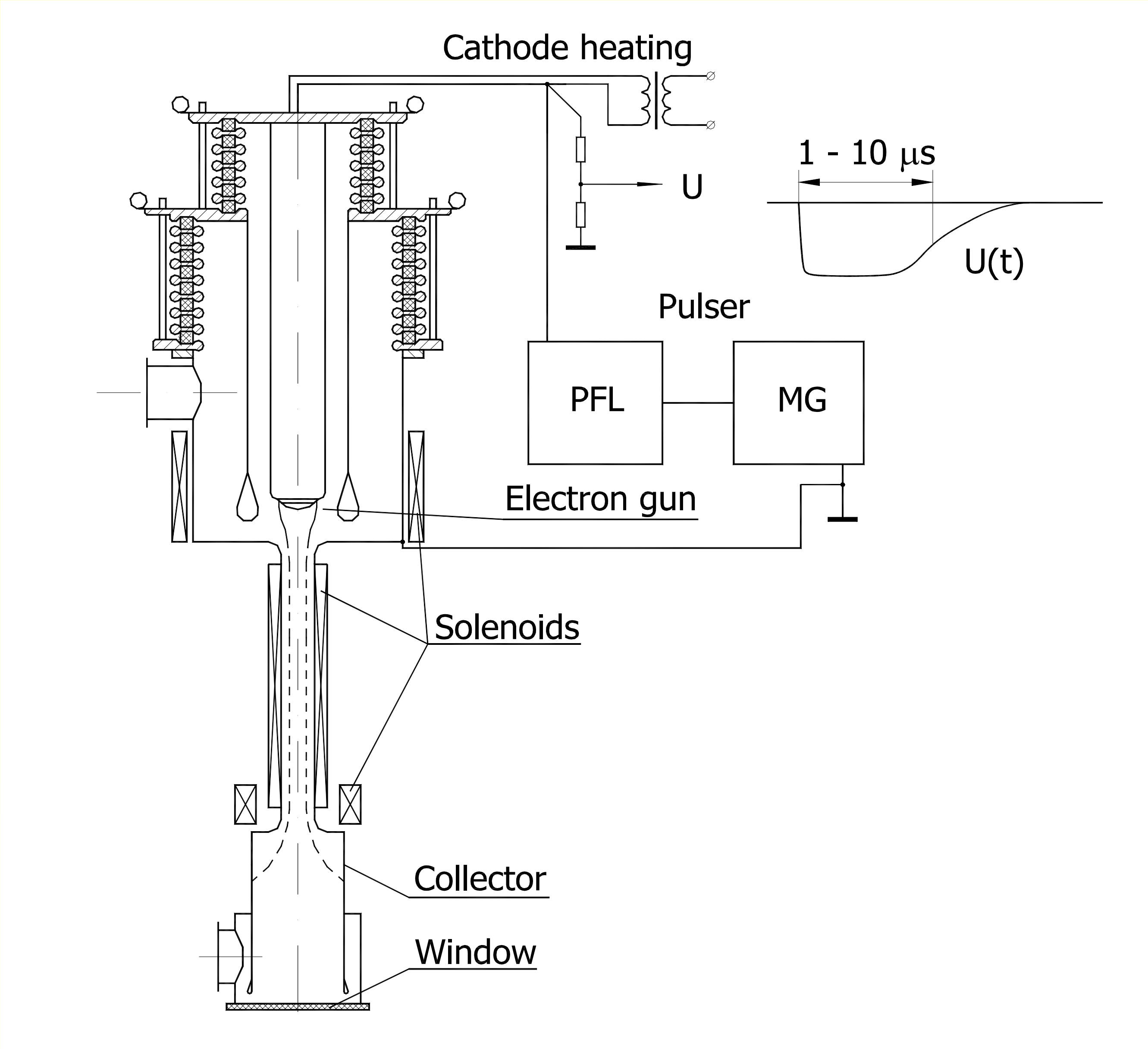


STAND

for testing gyroklystron

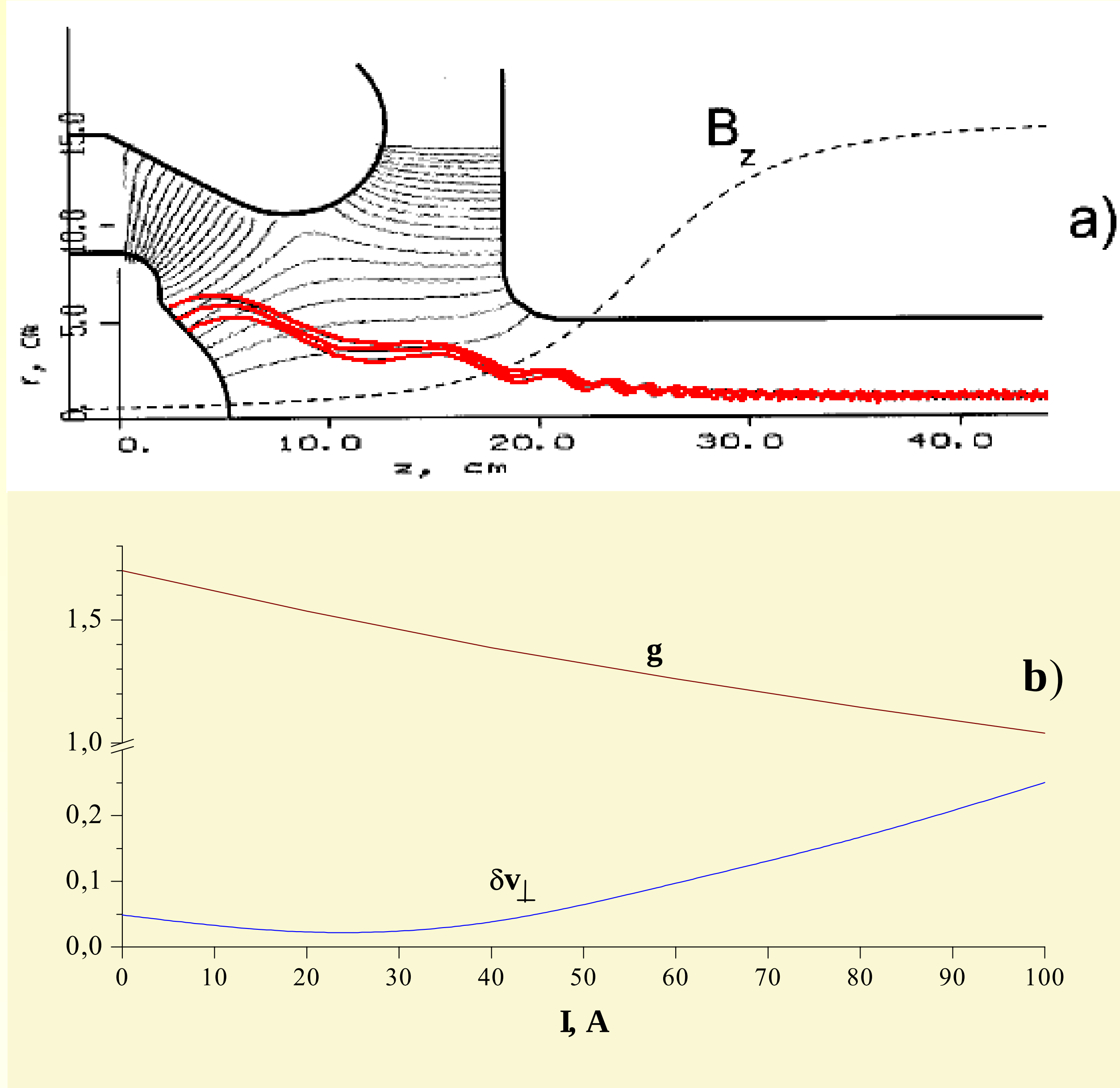
300 kV, 120 A / 1–10mks

300 kV/120A/(1-10) mks stand for testing gyroklystron



Triode magnetron-injection gun: design

IAP
GYCOM



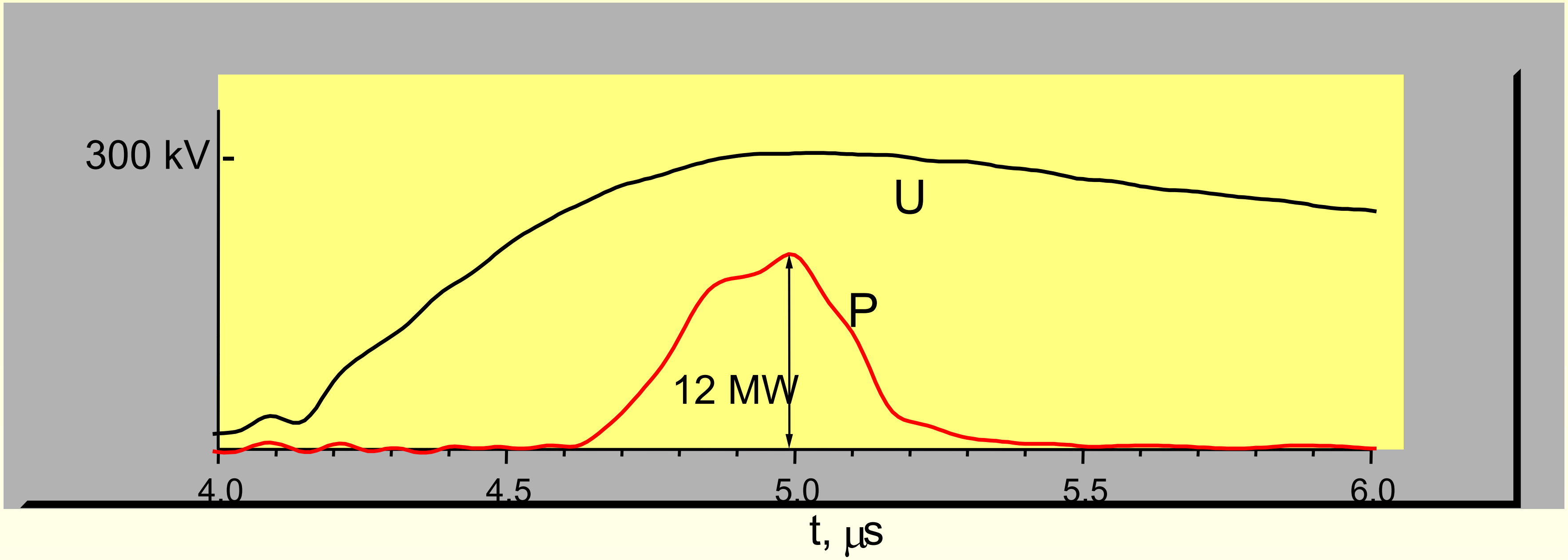
Pitch-factor and oscillatory velocity spread depending on current

Triode magnetron-injection gun 300 kV, 100 A

Cavity of 30 GHz TE_{53} gyrotron

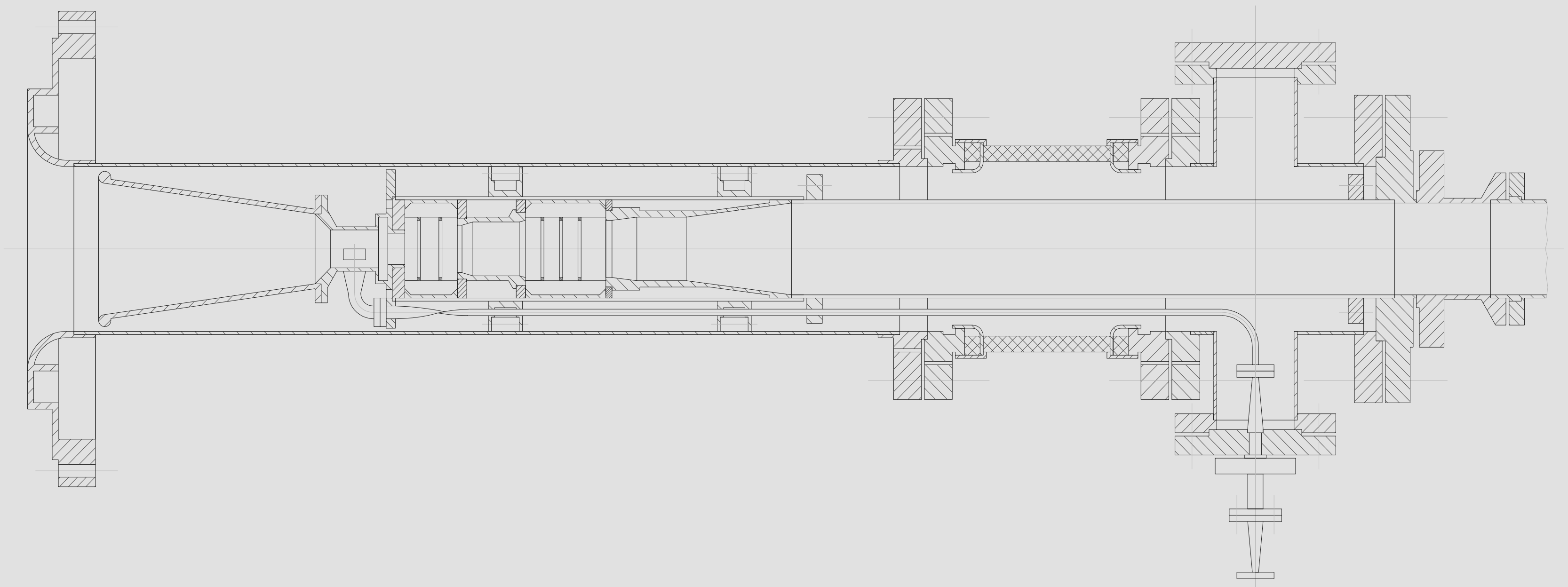
IAP
GYCOM

30 GHz TE_{53} gyrotron fed with 300 kV / 80 A electron beam



Power 12 MW, efficiency 50%

Project of 30 GHz gyroklystron operating at succession of $TE_{5.1}$, $TE_{5.2}$, TE_{53} modes



electron beam 280 kV, 60 A , $v_{\perp} / v_{II} = 1.3$

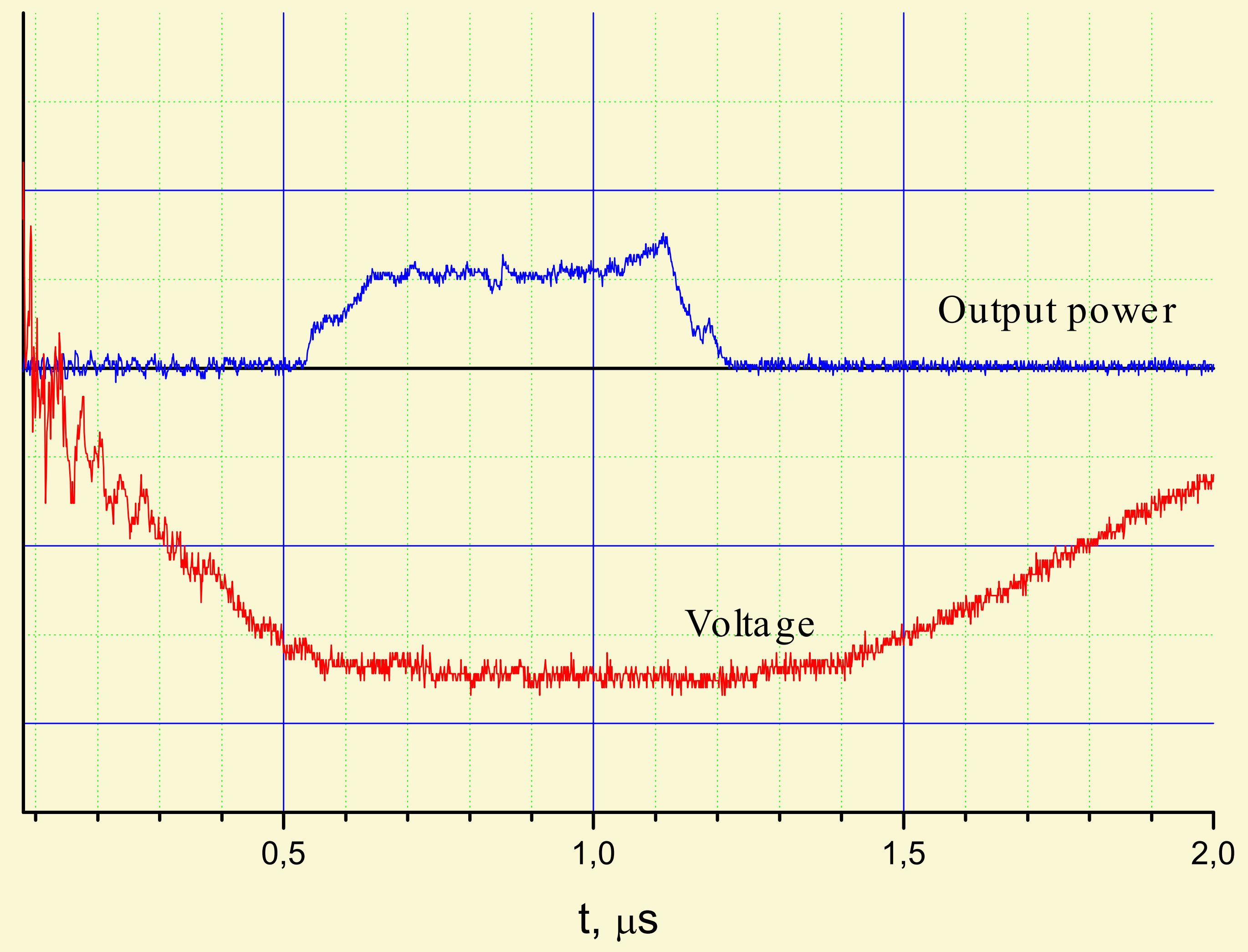
output power 5 MW

efficiency 30%

gain 30 dB.

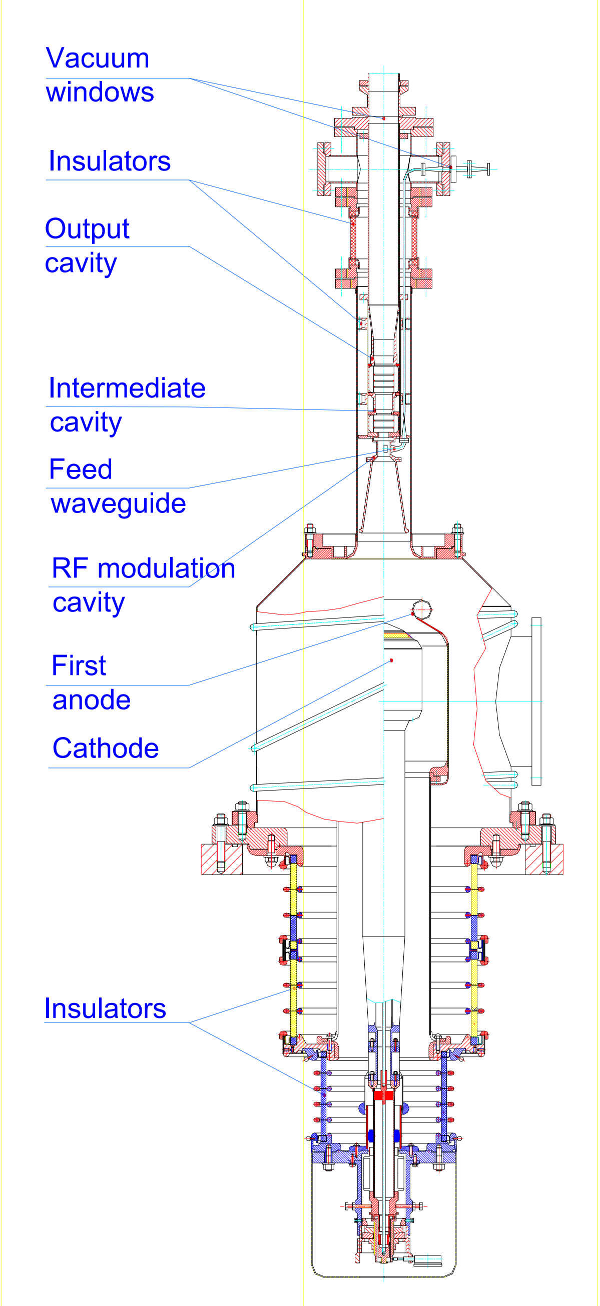
Collector, input and output waveguides of gyroklystron

Gyroklystron driven with 280 kV/75A beam – first tests: power 3.5 MW, efficiency 18 %, gain 27 dB

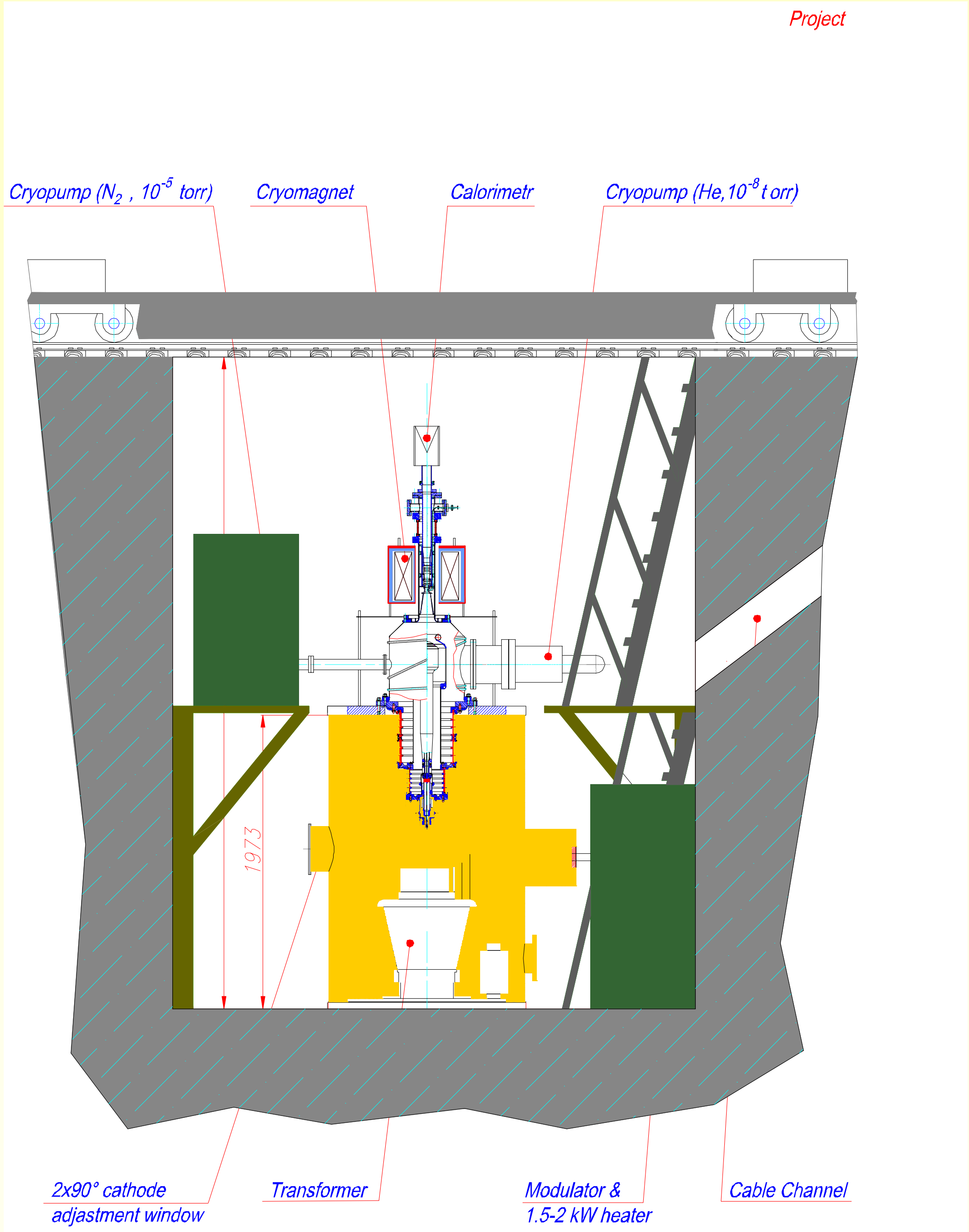


IAP
GYCOM

PROJECT
of 30 GHz / 30 MW / 1 mks
gyroklystron



IAP
GYCOM



Project of stand for testing 30 GHz / 30 MW / 1 μs / 10 pps gyroklystron