Millimeter Wave Microwave Devices for Electron Cyclotron Resonance Ion Sources

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OUTLINE

- Gyrotron. State of the art. ITER gyrotron.
- Moderate power gyro-devices. Examples.
  - Low frequency gyrotrons for technology. Second harmonic.
  - Higher frequency gyrotrons for tecnology. First harmonic.
  - Gyro-TWT
- Summary

Gyro-devices

Extraordinary high average power at mm and submm wavelengths

Main applications:

- ECW systems for plasma fusion installations (70-170GHz/1MW)
- Technological applications (ceramics sintering, … 24-80 GHz/3-30kW)
  CVD diamond films
- Plasma physics and plasma chemistry
  (multi-charged ion sources…)
- DNP spectroscopy (263, 394, 526 GHz, 10-100W)
- Radar systems ampl., 35; 94 GHz / 10kW av.

Discussions and studies

- Ultra violet sources submm, 100 kW, pulse
- Future linear accelerators amp. 30 GHz/100 MW/1mcs
- Medicine submm. 1-100 W
- ADS 94 GHz / >100kW
- ………..

Gyrotrons for ITER

The main specifications of the gyrotrons for ITER are described below:

Item	Specification
Nominal output power	≥ 0.96 MW at MOU output
Nominal frequency	170±0.3 GHz (TBD) including initial transient phase
Pulse length	400/1000/3600 sec (TBD)
RF power generation efficiency	≥ 50 % (with collector potential depression)
Gaussian content	> 95 % at output waveguide (63.5 mmϕ) of MOU
Power modulation	1 kHz (cathode); 5 kHz (anode)

For more details see Technical specifications (**https://user.iter.org/?uid=4GV66L**)

Russia, Japan, EU are (each team) to deliver 8 gyrotron sets to ITER:

Gyrotron, SC magnet, cathode and collector coils, support, water manifold, aix. power supplies, control system, …

The most developed gyrotrons are the devices for ITER. The gyrotron prototypes for ITER showed parameters corresponding to ITER requirements (see Table 1).
Now the main part of activity is enhancement of reliability and integration in ITER EC system

Table 1. Gyrotrons for ITER, 170 GHz

Main results	Institution/Company
1 MW / 55 % / 800 s and 0.8 MW / 57 % / 3600 s	JAEA/Toshiba, Japan
1 MW / 53 % / 1000 s and 1.2 MW / 53 % / 100 s	IAP/GYCOM, Russia

Achievement of ITER relevant parameters with RF gyrotron

In the last five years four gyrotron prototypes were fabricated and tested

with

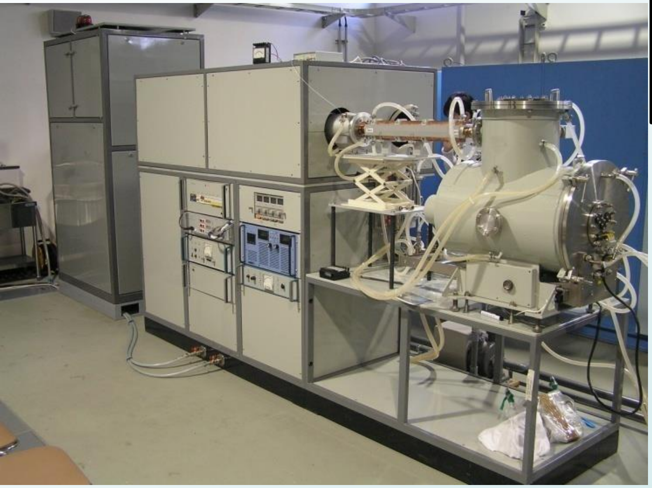
CRYOMAGNETICS (USA) and JASTEC (Japan) LHe–free magnets

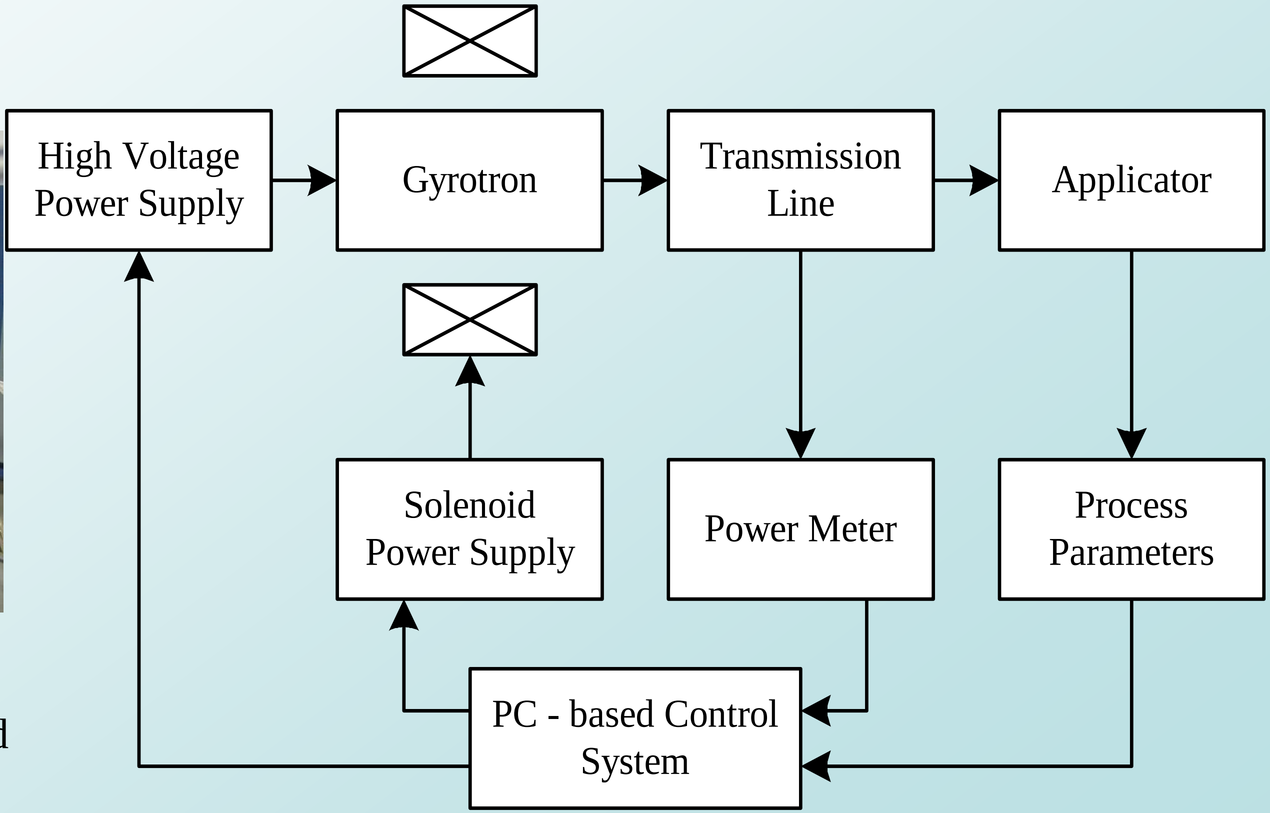
It is important to note that all gyrotrons demonstrate very similar output parameters

Also 140GHz; 110GHz, 105GHz, 82GHz, 70GHz, 60GHz, 42 GHz, …

Second Harmonic Gyrotrons for Technological Applications

At present more than 40 systems produced jointly by the IAP and Gycom Ltd. are operating throughout the world. Output power ranges are usually from 3 to 15 kW at frequencies 24 – 30GHz.

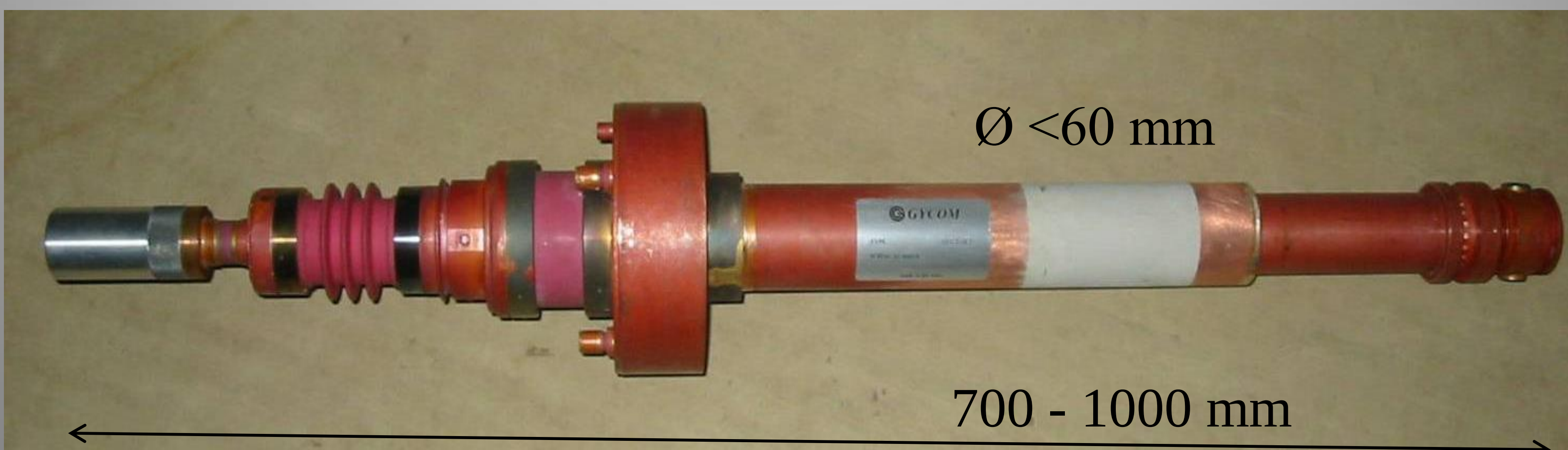




The systems are made up as standard computer-controlled setups with the feedback loop for power control.

Main features of low frequency CW gyrotrons

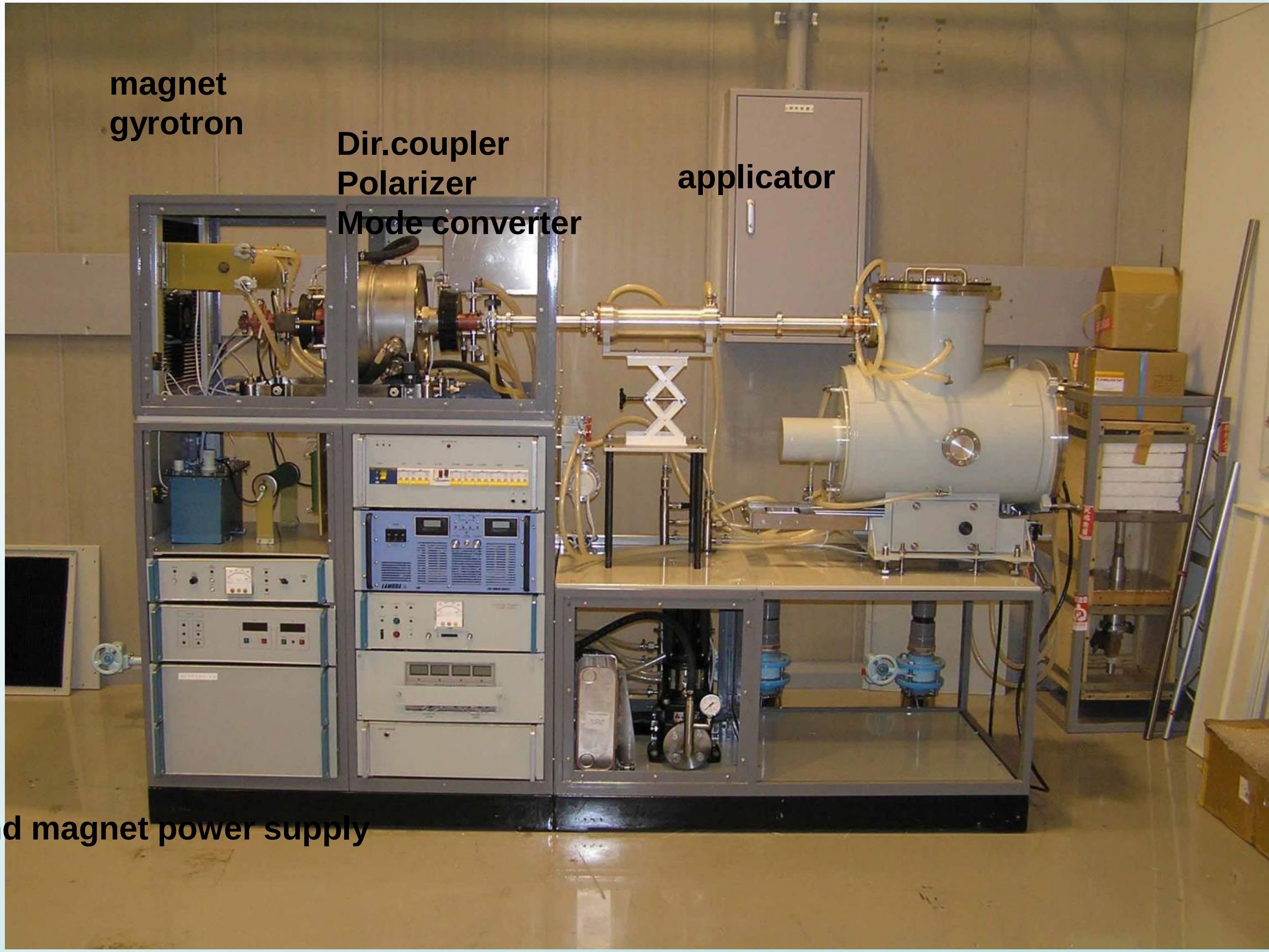
Output mode	waveguide operating mode
Number of harmonic	2
Type of the magnet	electromagnet with water or oil cooling, permanent magnet
Operating frequency	24 – 30 GHz
Output power	<25 kW
Accelerating voltage	<25 kV
Anode voltage	<10 kV
Beam current	<2.5 A



Low frequency CW gyrotron systems deliveries by GYCOM

			Freq., GHz	Power, kW	Year
1	Karlsruhe, Germany	FZK	30	10	1994
2	Los Alamos, USA	LANL	30	10	1996
3	Albuquerque, USA	Sandia NL	30	10	1996
4	Livermore, USA	General Atomics	30	10	1997
5	Menhang, China	IAPh CAS	30	10	1998
6	Fukui, Japan	FIR	24	3	2001
7	Grenoble, France	IN2P3	28	10	2003
8	Osaka, Japan	Osaka Univ.	24	3	2003
9	Osaka, Japan	Osaka Univ.	24	3	2004
10	Ochiai, Japan	Alloy Industries Inc.	28	10	2004
11	Osaka, Japan	Kinki Univ.	24	3	2005
12	Matsue, Japan	SIIT	24	3	2005
13	Fukui, Japan	FIR	28	15	2006
14	Albuquerque, USA	Thor Technologies, Inc.	24	5	2006
15	Kawasaki, Japan	Isman J Corp.	24	3	2006
16	Sendai, Japan	Tohoku Univ.	24	3	2006
17	Darmstadt, Germany	GSI mbH	28	10	2007
18	Okayama, Japan	Okayama Univ.	24	3	2007
19	Milan, Italy	IFP	28	15	2008
20	Lanzhou, China	IMP CAS	24	7	2009
21	Novosibirsk, Russia	CCU NSU	24	5	2009
22-30					2010-2014

5 kW 24 GHz Gyrotron-based system for materials processing



5 kW 24 GHz system with a permanent magnet

f ≤ 40 GHz - “warm” (water or oil cooled) solenoid or permanent magnet
(magnetic field for second harmonic operation ~ 0.5 T)

f ≥ 40 GHz - superconducting solenoid (LHe or LHe- free, last one consumes 5-10 kW)

Transmission line

Oversized transmission lines ($a_\perp >> \lambda$) made as a set of quasi-optical mirrors, **multimode waveguides** and often their combination

DC breaks 20-60 kV

Efficiency of the millimeter-wave power transport through lines is normally 0.95-0.98. **Very advanced synthesis codes** are used for the design of TL.

Design of a transmission line depends on the trajectory, functions and field structure a **customer wants** to have in the applicator

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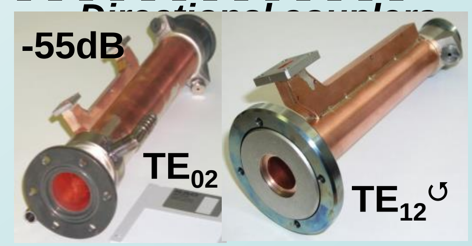
Mode converters
with efficiency over 0.99

TE_{02}
TE_{12}

TE_{11}



Some TL components

Polarizers

Bends with efficiency over 0.99

Example (2009)

The major output characteristics of the electron cyclotron resonance ion sources (ECRIS), such as the total ion current and the mean ion charge, could be improved with an increase in frequency of the applied microwave power. Recently experimental verification of the frequency scale up has been extended to frequencies of 28 GHz.

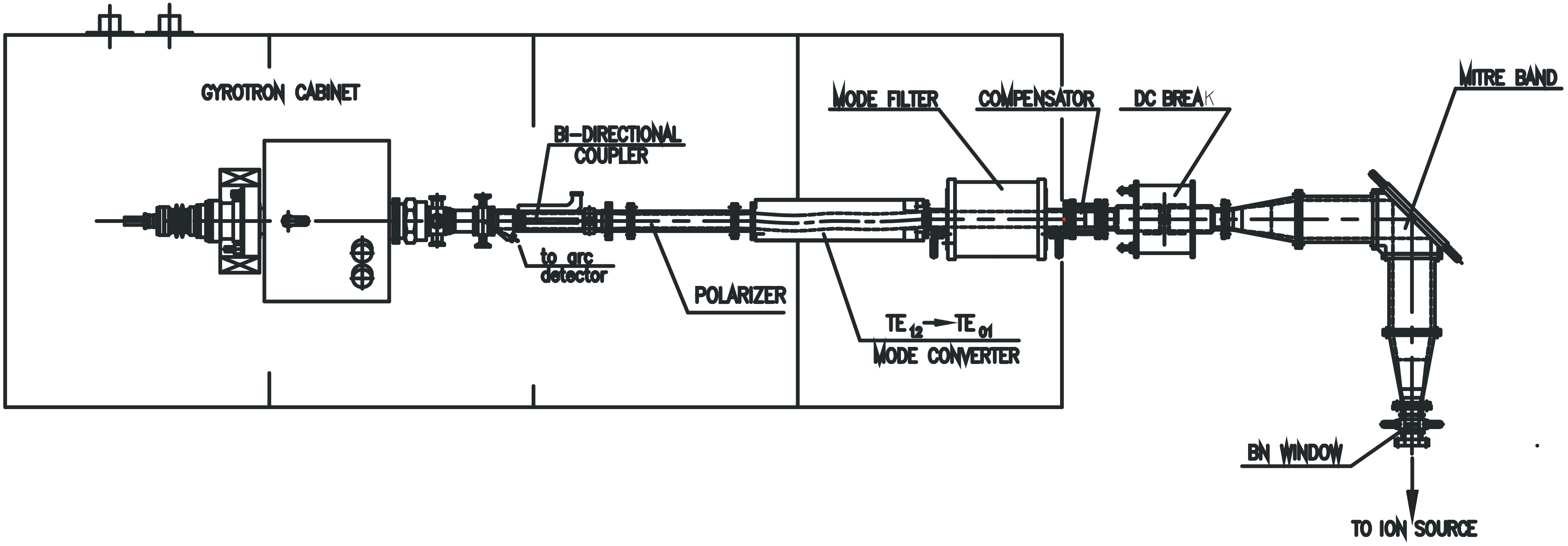
Microwave power of the order of several or tens of kilowatts in CW regime, required for feeding of ECRIS aimed to practical use, can be provided at frequencies of about tens GHz with gyrotrons only.

Gyrotron-based system with output power of 7 kW at frequency of 24 GHz has been developed by the Institute of Applied Physics jointly with GYCOM Ltd for powering the SECRAL Superconducting ECR Ion Source of the Institute of Modern Physics, China Academy of Sciences, Lanzhou.

MAJOR TECHNICAL CHARACTERISTICS

Operating frequency	**24 GHz ± 50 MHz**
Operation regime	**either CW or pulse mode**
Output microwave power	**0.1 kW – 7 kW, smoothly controlled**
Output mode/Mode entering ion source	**TE_{12} / TE_{01}**
DC break in transmission line	**40kV**
Mode purity (whole system)	**98% minimum TE_{01}, 2% other modes**
Power adjustability	**100 W … 7 kW with an increment 25 W**
RMS ripple	**≤ 1%**
Power stability vs time*	**better than 0.25 dB/24 h**
Power stability vs temperature*	**better than 0.05 dB/°C in the range 20 °C – 30 °C**
Power stability vs mains voltage*	**less than 1% for a mains variation of ± 20 V**
Pulse mode operation	
Fall time RF / Rise time	**< 30 µs / < 500 µs**
Pulse duration RF	**5 – 100 ms or CW**
Repetition rate	**1 – 10 s^{-1}**

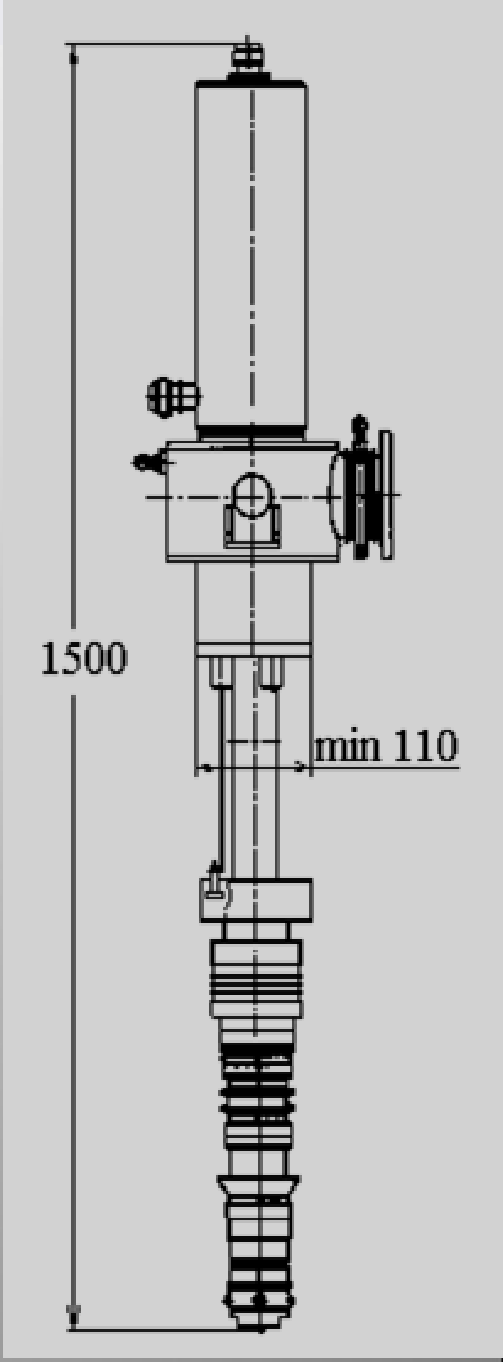
24 GHz gyrotron for ECRIS. Microwave components of the setup.



Example (2009)

24 GHz gyrotron system for ECRIS at factory tests

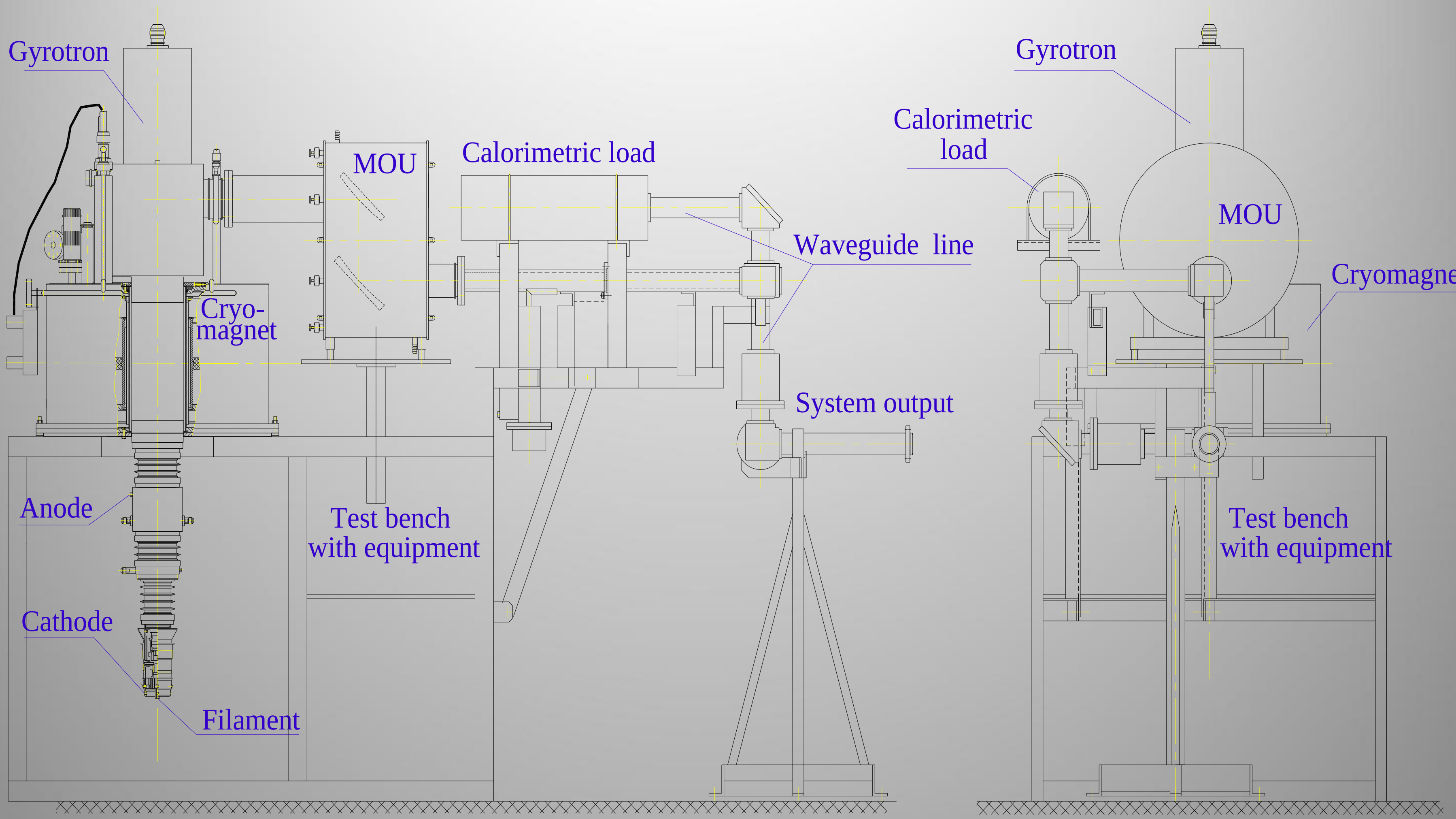
Frequency and power rise of CW gyrotrons by operation at first harmonic in cryomagnets



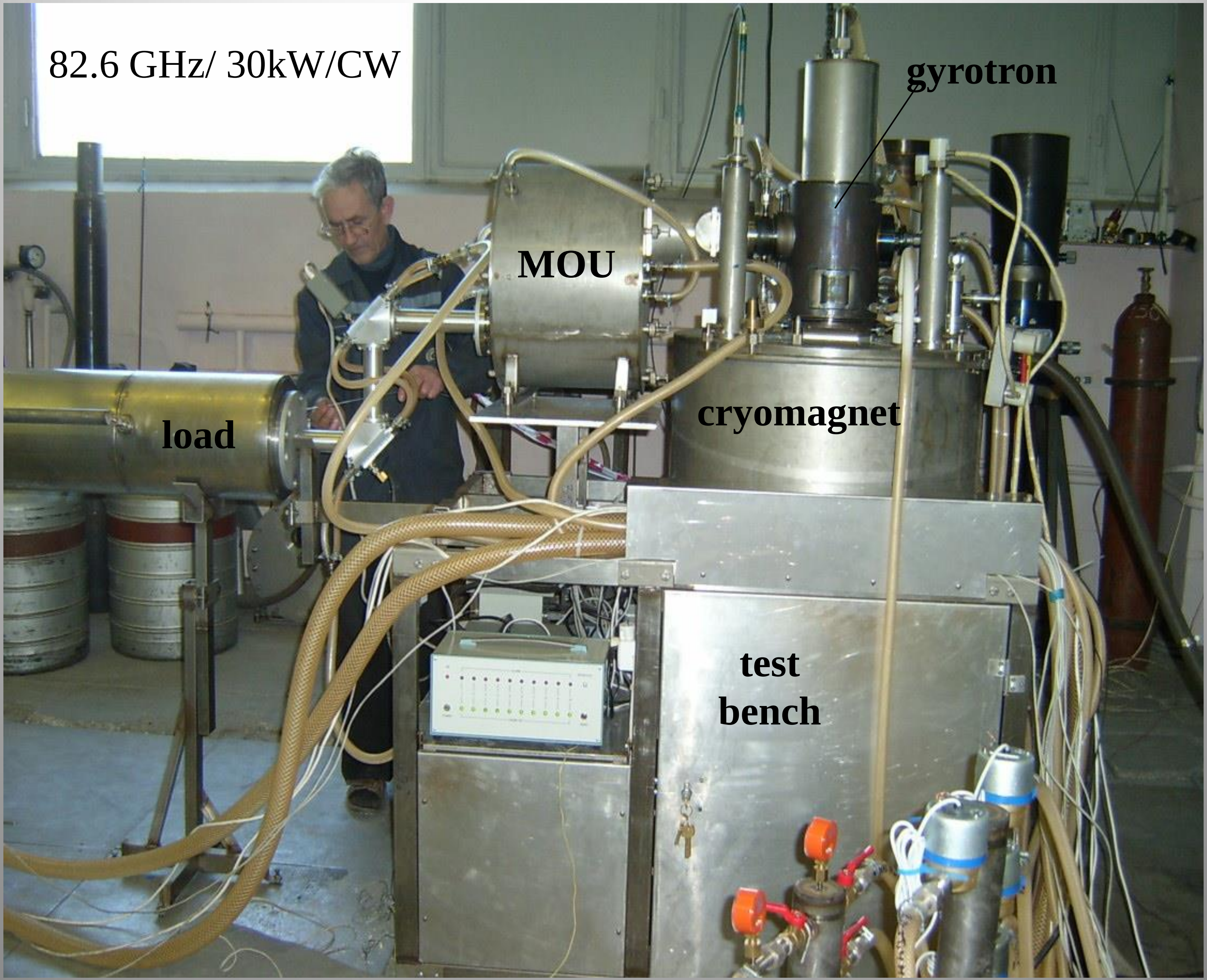
Main features of CW gyrotrons at cryomagnets

- triode-type electron gun
- gyrotron is installed in cryomagnet warm bore from cathode side
- lateral direction of output Gaussian wave beam by quasi-optical build-in converter
- setting diameters in cryomagnet bore 110 – 140 mm
- efficiency of gyrotron 50-60 %

Typical scheme of gyrotron system



Assembling of 30 kW CW gyrotron complex. Gyrotron block.

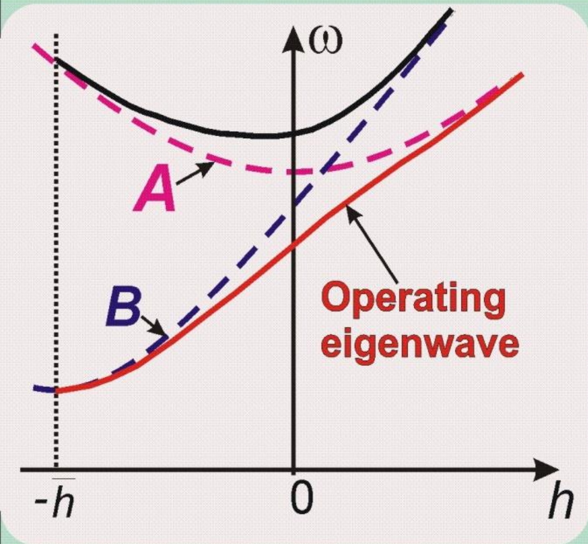


Gyro-amplifiers

More difficult than oscillators

- Helical-waveguide gyro-TWTs
  - principles
  - recent activity at IAP/GYCOM

Realization of the Favourable Wave Dispersion: Waveguide with Helical Corrugation



$$\vec{E}_A = \left(\vec{a}_+ e^{-ih_A z} + \vec{a}_- e^{ih_A z}\right) e^{i(\omega t - m_A \varphi)}$$

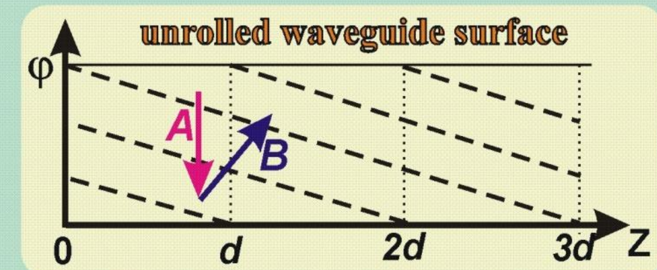
$$\vec{E}_B = \vec{b}\, e^{-i h_B z}\, e^{i(\omega t + m_B \varphi)}$$

A and *B* are circular polarized modes of unperturbed circular waveguide

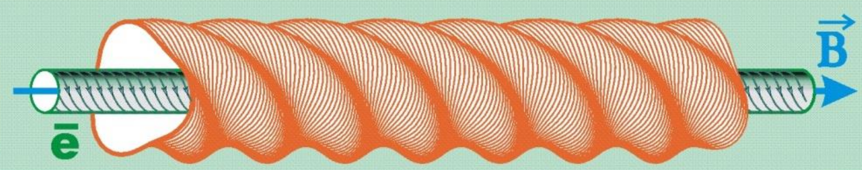
$h_A \ll \omega/c$, $h_B \sim \omega/c$

$\bar{m} = m_A + m_B$, $\bar{h} \approx h_B$

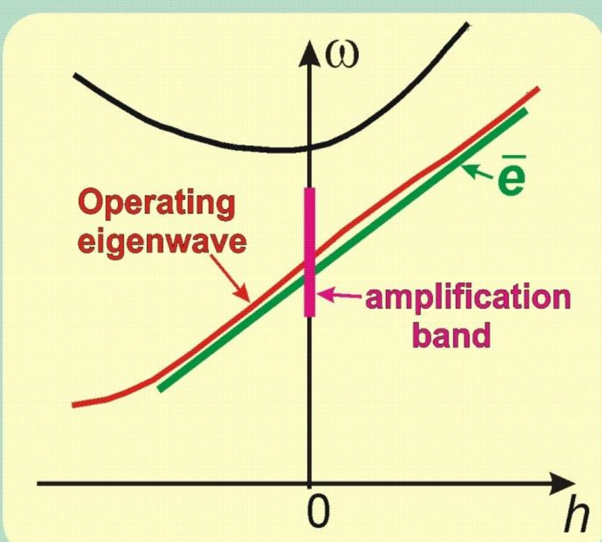
$$r(\varphi, z) = r_0 + l\cos(\bar{m}\varphi + \bar{h}z)$$

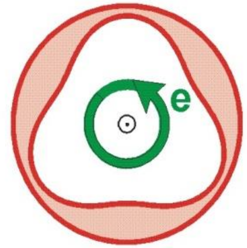


Gyro-TWT



Gyro-BWO





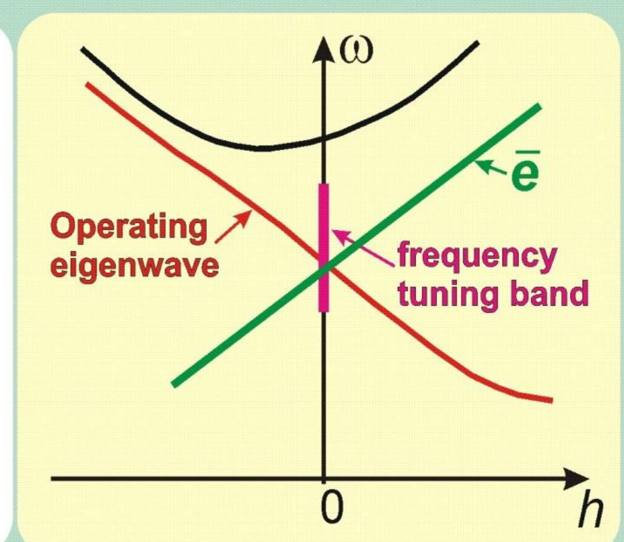
3-FOLD HELICAL CORRUGATION

axis-encircling electron beam

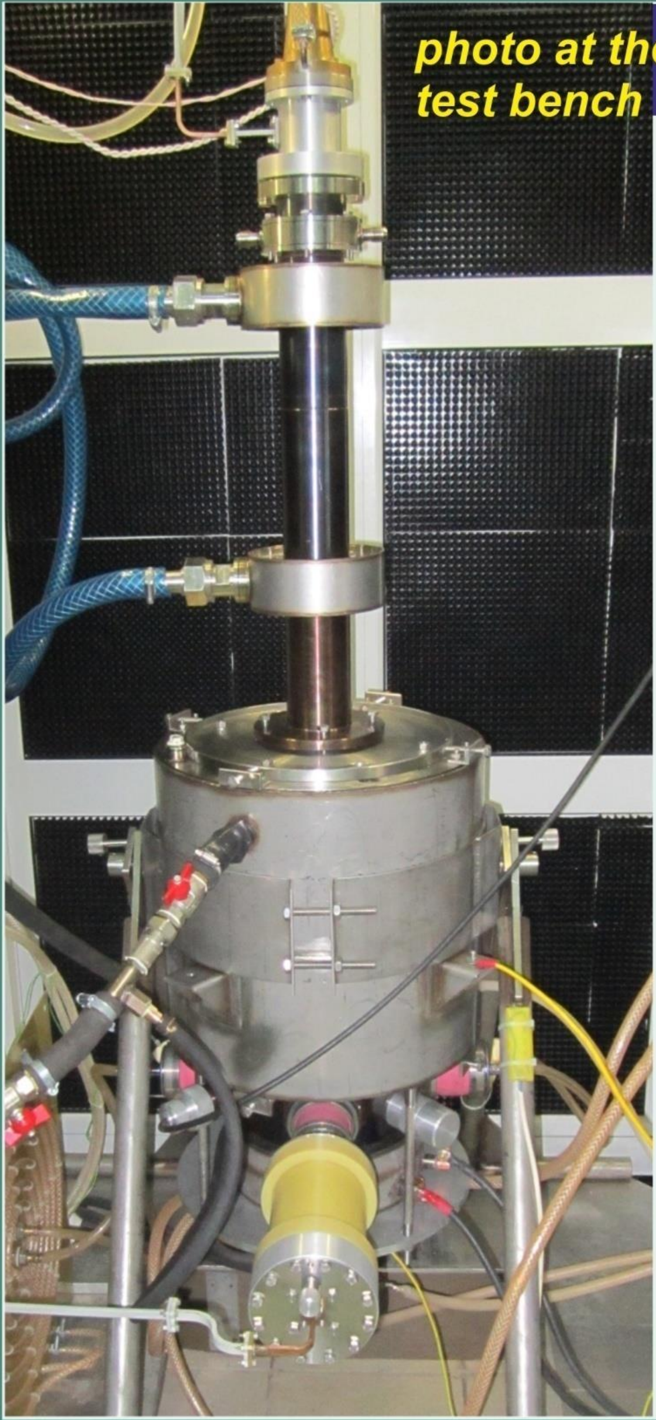
mode *A* - $TE_{2,1}$

mode *B* - $TE_{1,1}$

2nd cyclotron harmonic interaction



Pulsed Gyro-TWT

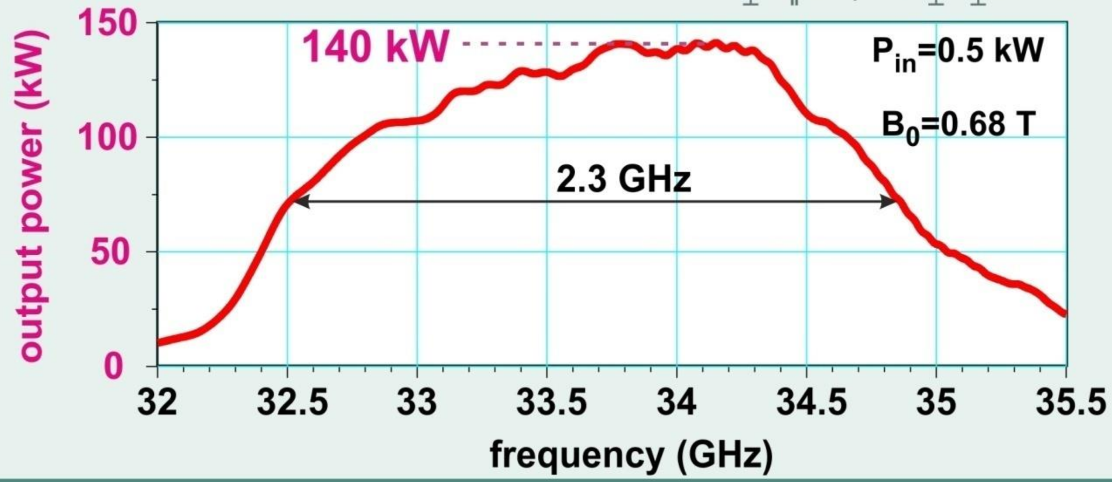


Design parameters

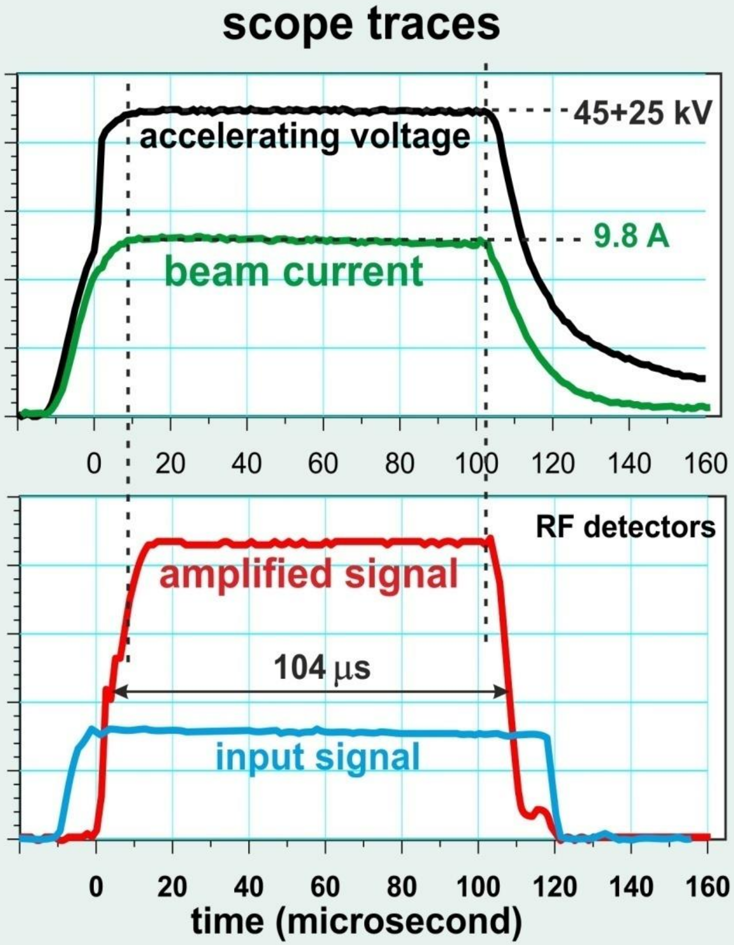
Accelerating voltage................. 70 kV
Retarding (SSDC) voltage ...... >20 kV
Beam current .... < 10 A
Magnetic field .... 0.7 T
Input RF power.......................... ~1 kW
Pulse length.................................100 μs
Max. average beam power ....63 kW
Max. average output power ....15 kW

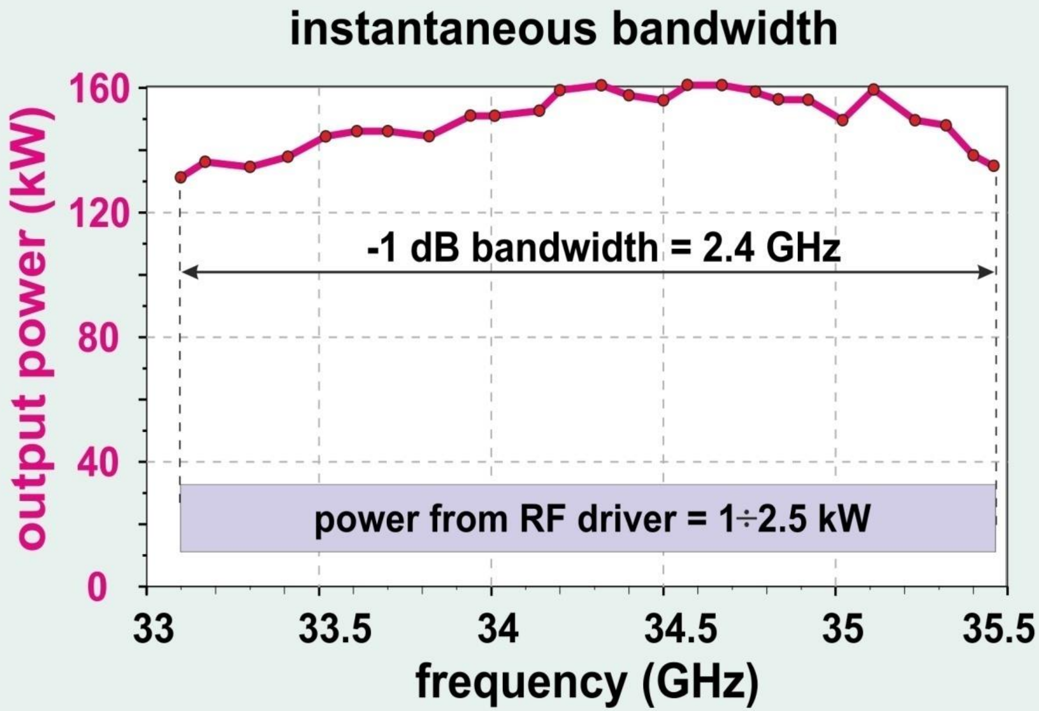
Simulation results

e-beam: E=70 keV, I=10 A
$v_\perp/v_\parallel=1$; $\Delta v_\perp/v_\perp=0.4$



Pulsed Gyro-TWT. Low duty results.





pulse repetition frequency
= 10 Hz (duty-factor = 0.1%)

limited by the high-voltage modulator and RF driver

Max. pulsed output power - 160 kW

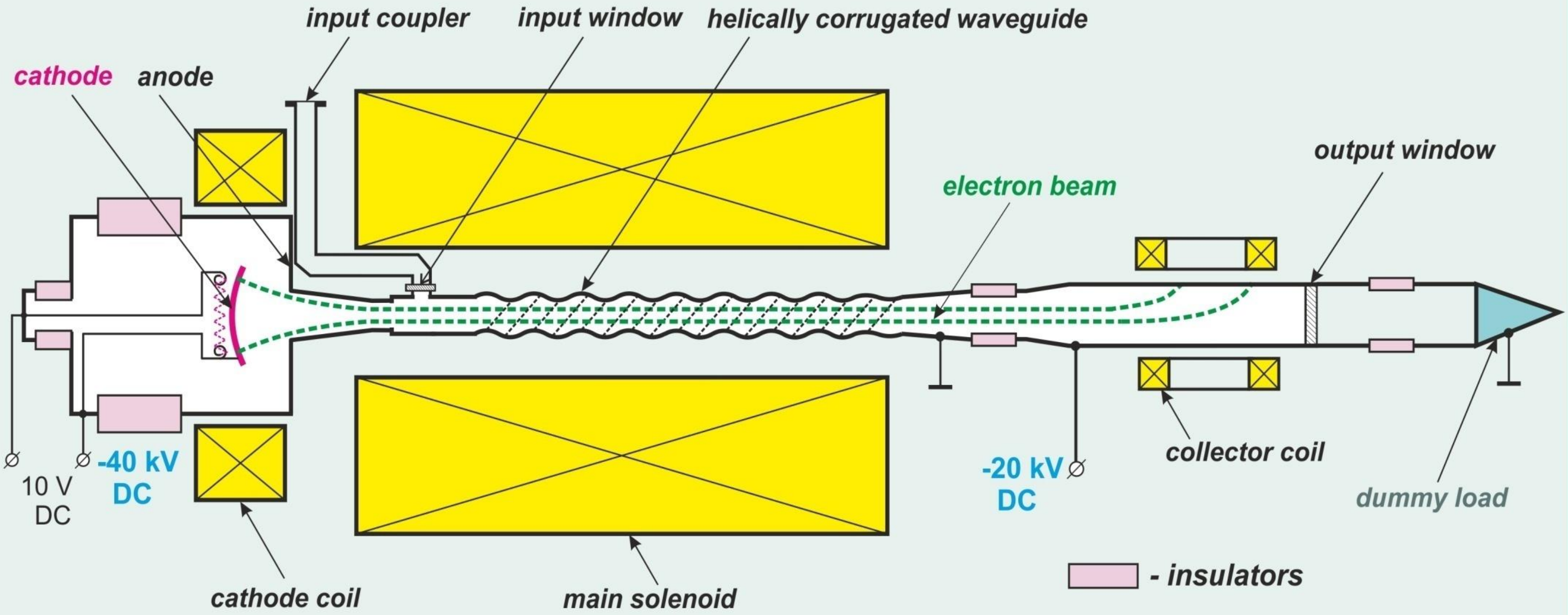
Main high-voltage power supply- 45 kV×10 A

Low-current power supply - 25 kV×10 mA

Max. electron efficiency = 160/450.2≈0.36

CW Gyro-TWT

Scheme

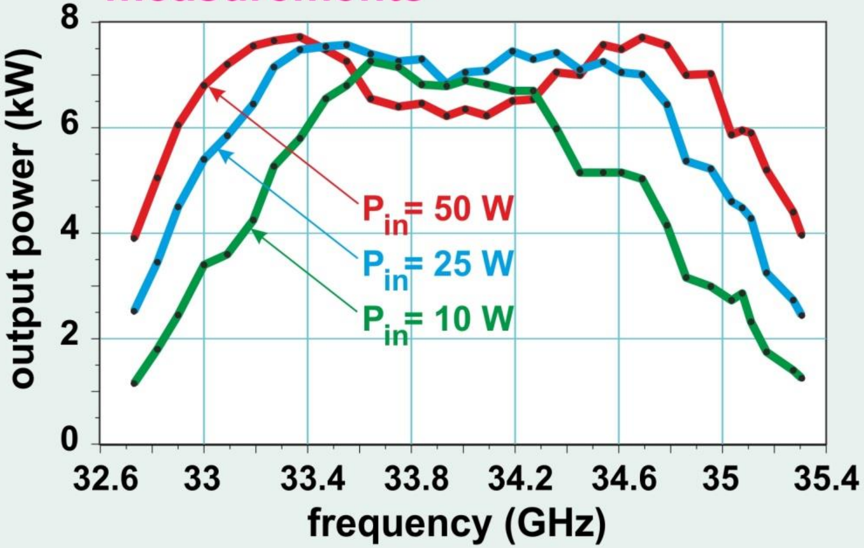


50% energy recovery using a single-stage depressed collector (SSDC)

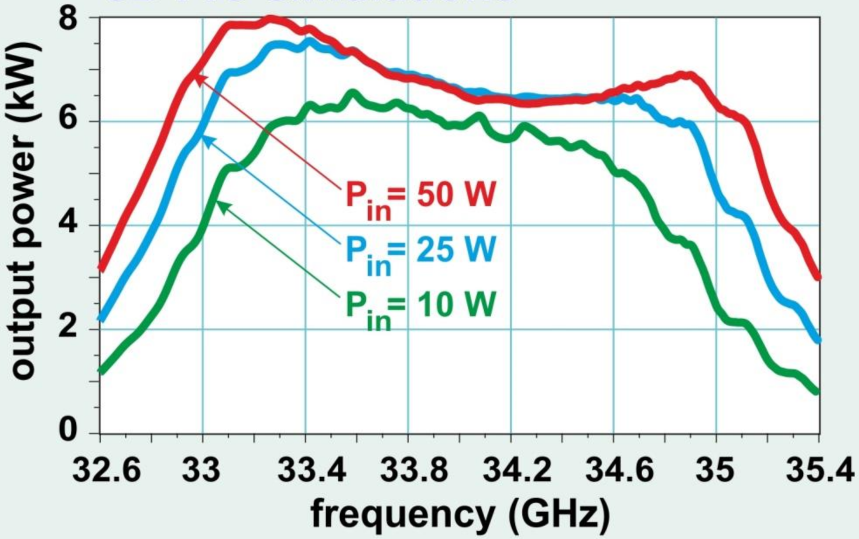
- **anode and tube body are grounded**
- **collector is under retarding potential**
- **accelerating voltage is applied to the cathode by a low-current highly-stabilized 40-kV DC power supply**

CW Gyro-TWT. Experimental results.

measurements



3D PIC simulations



e-beam at the simulations: E=40 keV, I=1.5 A

$v_\perp/v_\parallel$=0.9; $\Delta v_\perp/v_\perp$=0.35

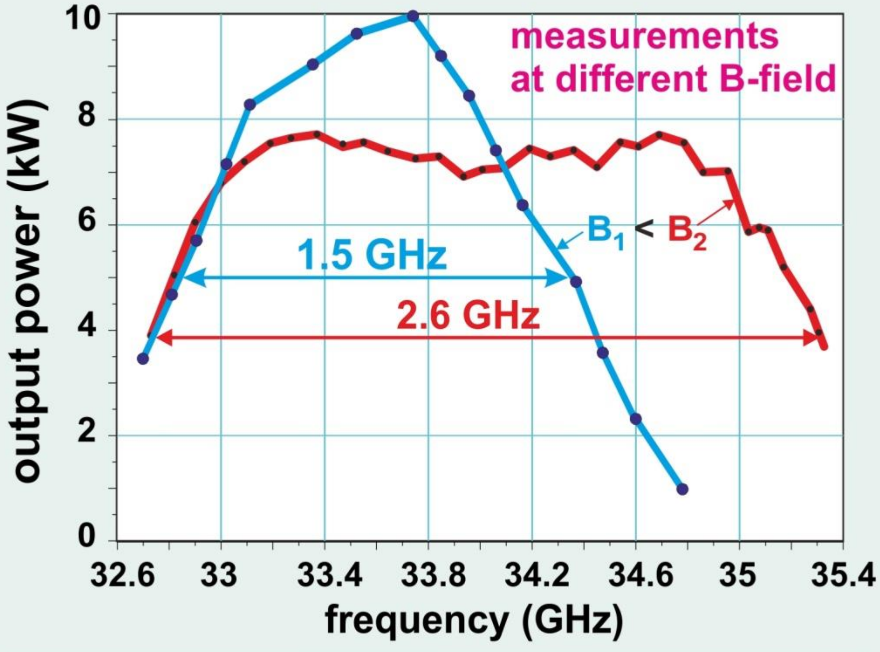
External parameters:

Main power supply.................20 kV × 1.5 A= 30 kW

Low-current power supply...40 kV × 30 mA=1.2 kW

Solenoid power supply.......180 V×125 A = 22.5 kW

RF driving source (preamplifier)........100 W (max.)



P_{max}= 10 kW; $\Delta f_{-3\ dB}$= 1.5 GHz

P_{max}= 7.7 kW; $\Delta f_{-3\ dB}$= 2.6 GHz; $\Delta f_{-1\ dB}$= 2.1 GHz

Max. electron efficiency = 10/31.2 ≈ 0.32

Summary

Gyrotrons by IAP/GYCOM :

Fusion

- 170 GHz, 1 MW/1000sec + other frequencies

Technology (examples)

- 24 GHz ; 28 GHz/10kW/ CW
- 82.6 GHz / 25 kW/ CW
- 60 GHz double regime: 300kW /0.1-10 ms and 20 kW/CW
- 300 GHz/ 3 kW/ CW

- Ka band / 2GHz/ 7kW /CW amplifier

Gyro-oscillators: any frequency (20-200 GHz); any power (1kW-1MW)
Gyro-amplifiers : 20-40 GHz/ ~10 kW/ δf~ 2 GHz

Gyrotron developers are waiting for ECRIS requests