The report includes materials of three papers:

Performance of 170 GHz high-power gyrotron for CW operation
A. Kasugai, Japan gyrotron team

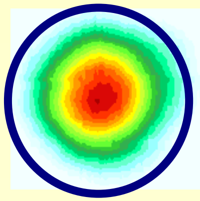
Development of Steady-State 2-MW 170-GHz Gyrotrons for ITER
B. Pioszuk, EU gyrotron team

New Results in Development of MW Output Power Gyrotrons for Fusion Systems
A.G. Litvak, Russia gyrotron team

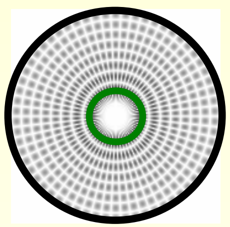
Outline of the talk

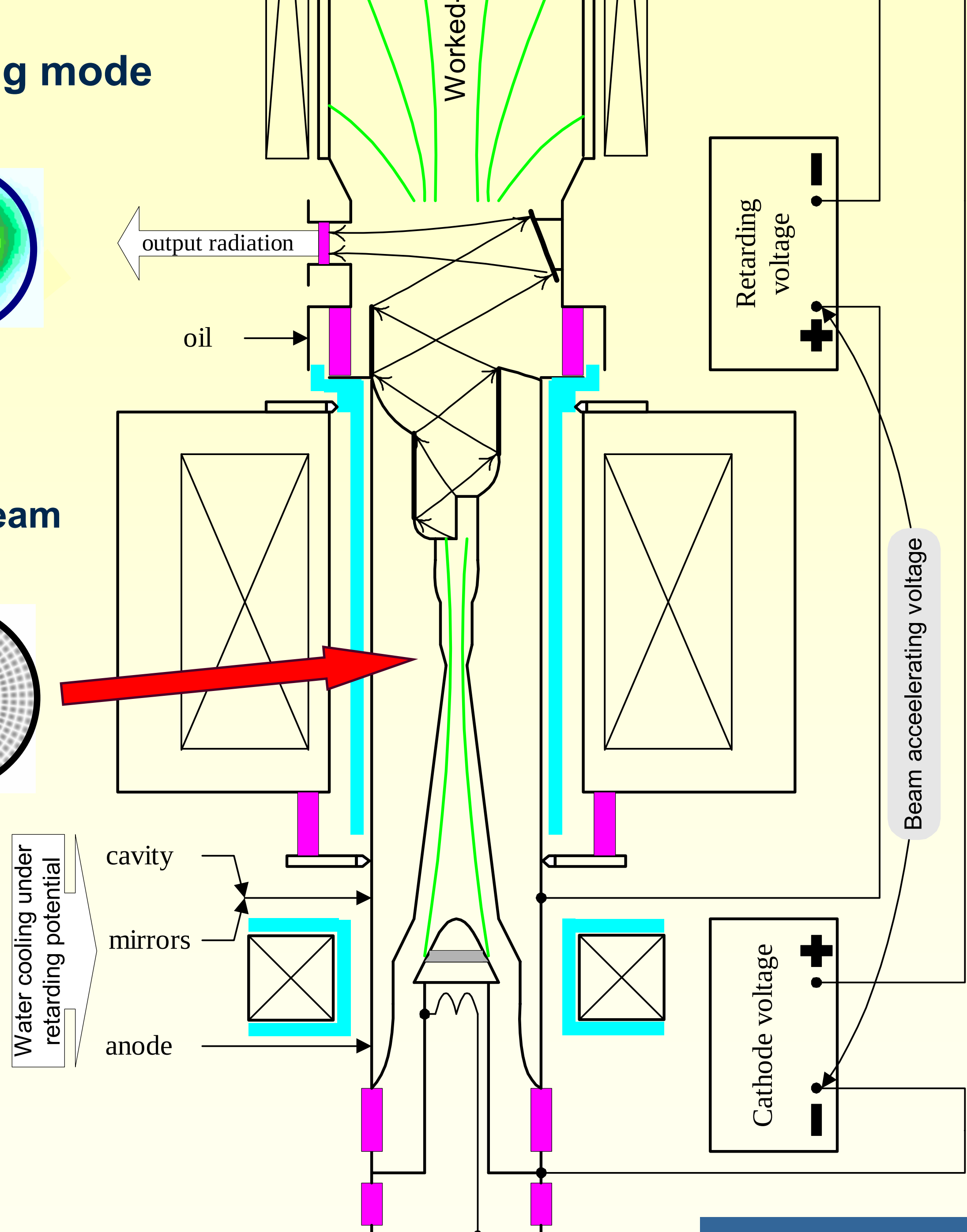
I. Main problems in development of MW gyrotrons
II. Conventional gyrotrons for ITER
III. Study of advanced gyrotrons concepts
IV. Gyrotrons for running and near future installations
V. Summary

Operating mode



Output wave beam





$TE_{31.8}$, $TE_{25.10}$
Ø ≈ 20 λ

During last 10 years principal steps were made in development of MW 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%.

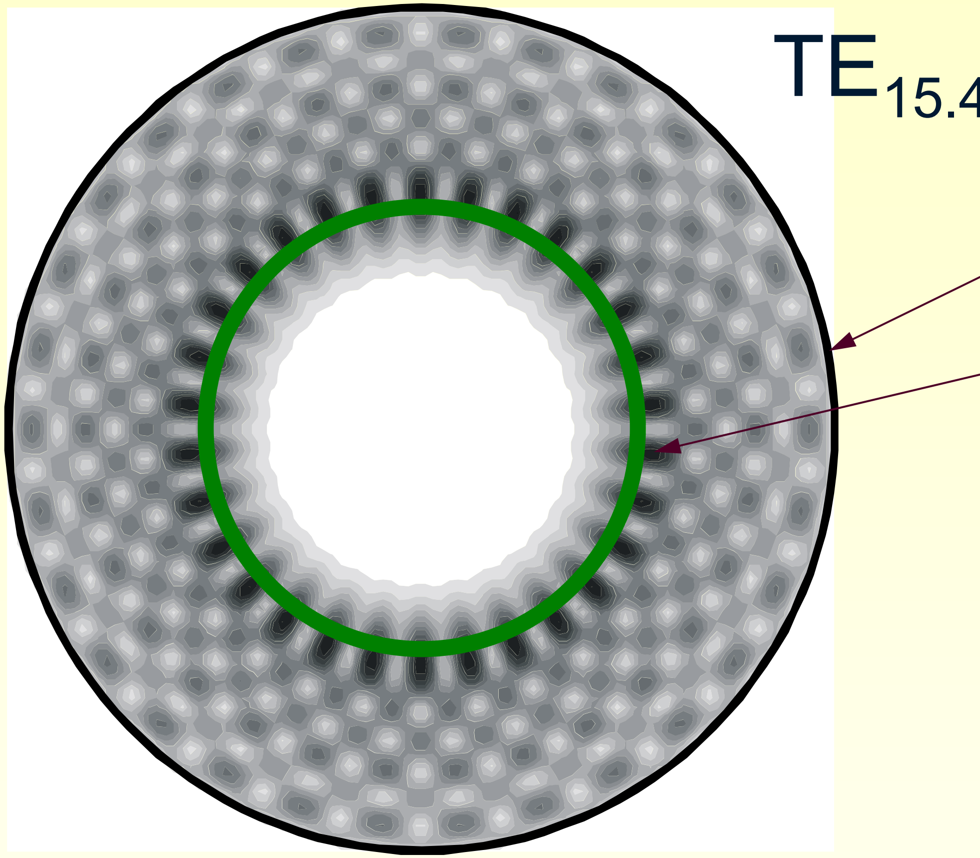
- Gyrotron windows based on CVD diamond disks with a very low absorption and very high heat conductivity were developed.

- 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

TE25.10
TE31.17



⇕ λ/2

XXL e - beam size
XXL cavity size
↓
High power

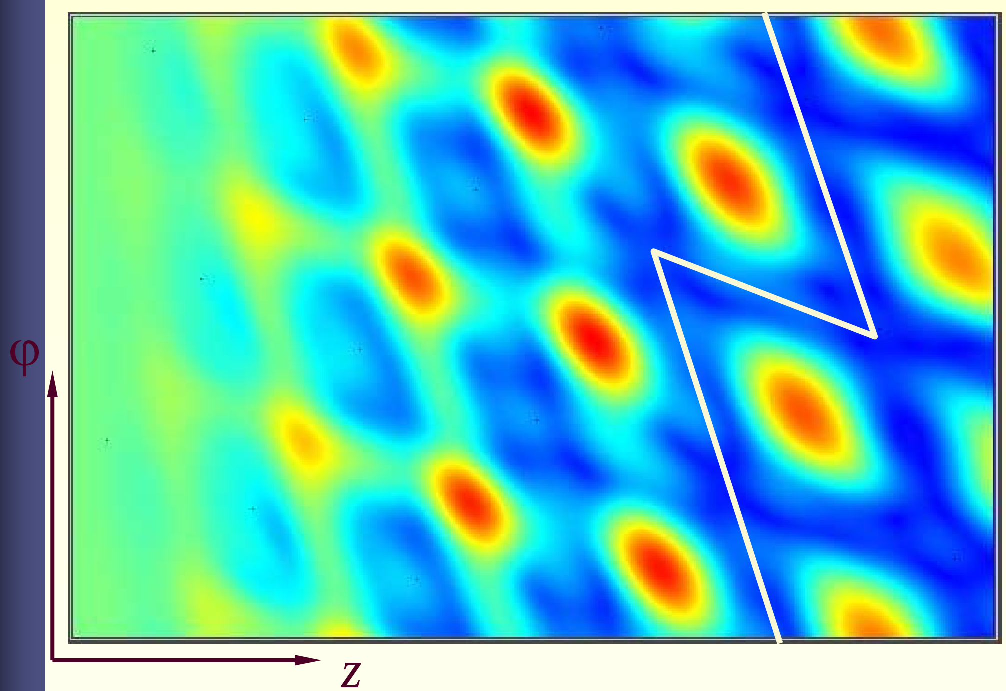
The specific power is limited for gyrotron cavity configuration as $\Delta P/\Delta S < 2\text{-}3\ kW/cm^2$ and power enhancement is linked with cavity size increase.

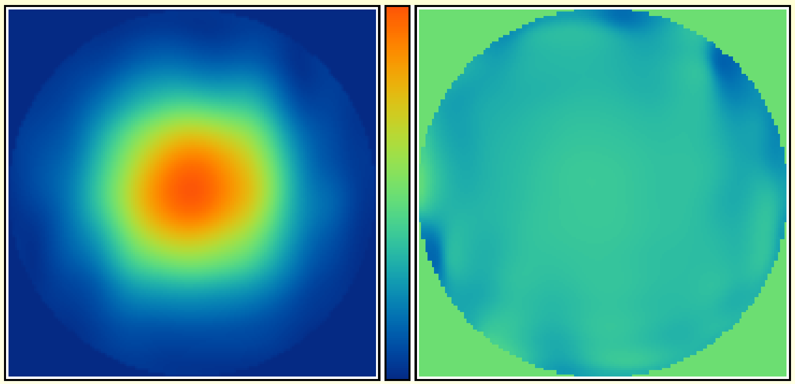
GYCOM's 170 GHz Gyrotron. New mode converter

- Pre-shaping
- Slightly conical launcher

Field amplitude distribution at the gyrotron window

H_z field component distribution at the converter wall





Gaussian mode content: η=99,49 %
(Ax=14.9мм, Ay=14.68мм)

Diffraction losses: $\Delta P < 2\%$

Diamond window mounted in 170 GHz ITER gyrotron

I. Conventional gyrotrons for ITER

Specification: 1MW/170GHz/1000sec

Results achieved:

Japan team

0.5MW/ 100sec; 0.75MW/17 sec; 0.9MW/9sec

Limitations: overheating of the insulator, current decrease

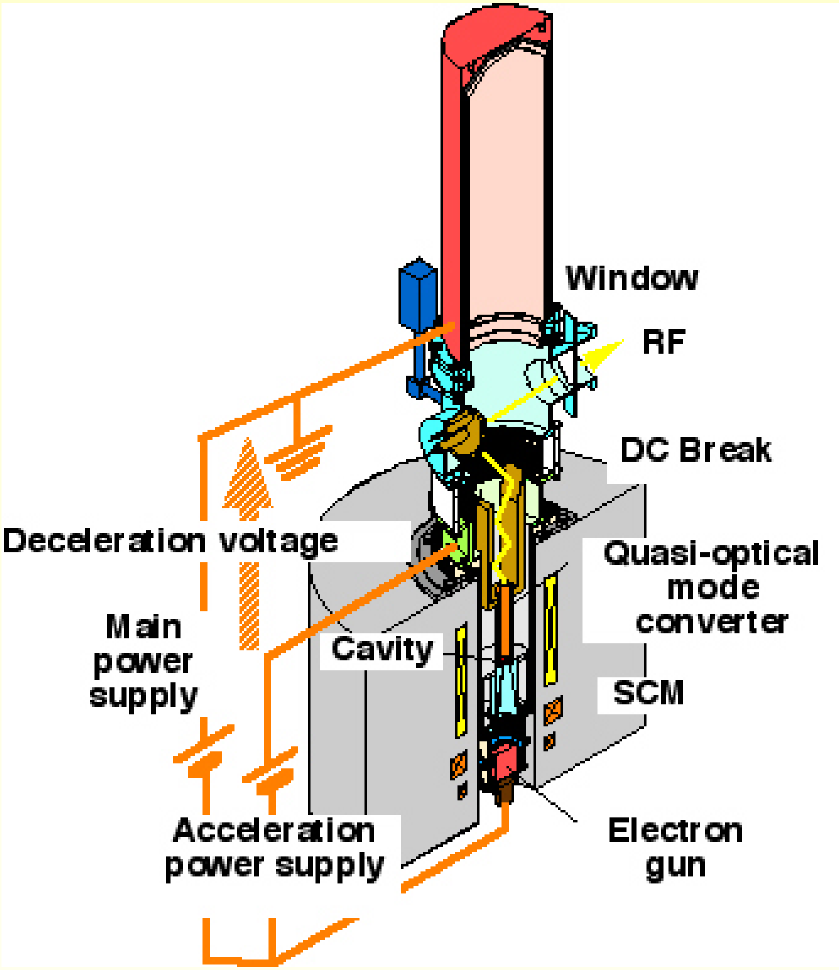
Russian team

0.5MW/ 80sec; 0.7 MW/40 sec; 0.85MW/19sec

Limitations: load; overheating of relief window

Conventional gyrotrons for ITER (JAERI)

Photograph of 170GHz gyrotron.
Height is ~3m and weight is ~800kg

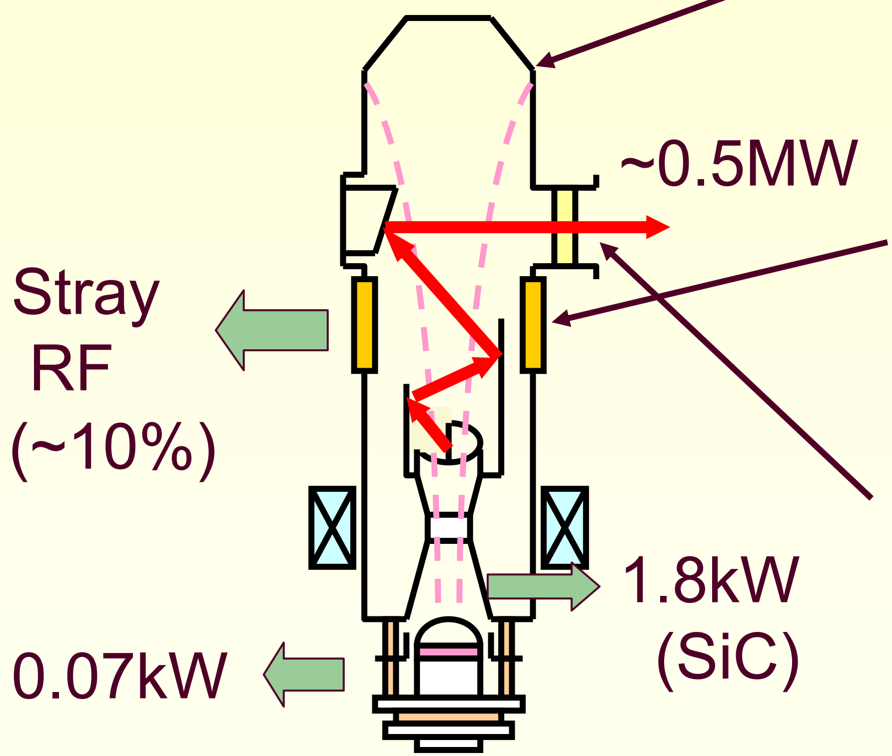


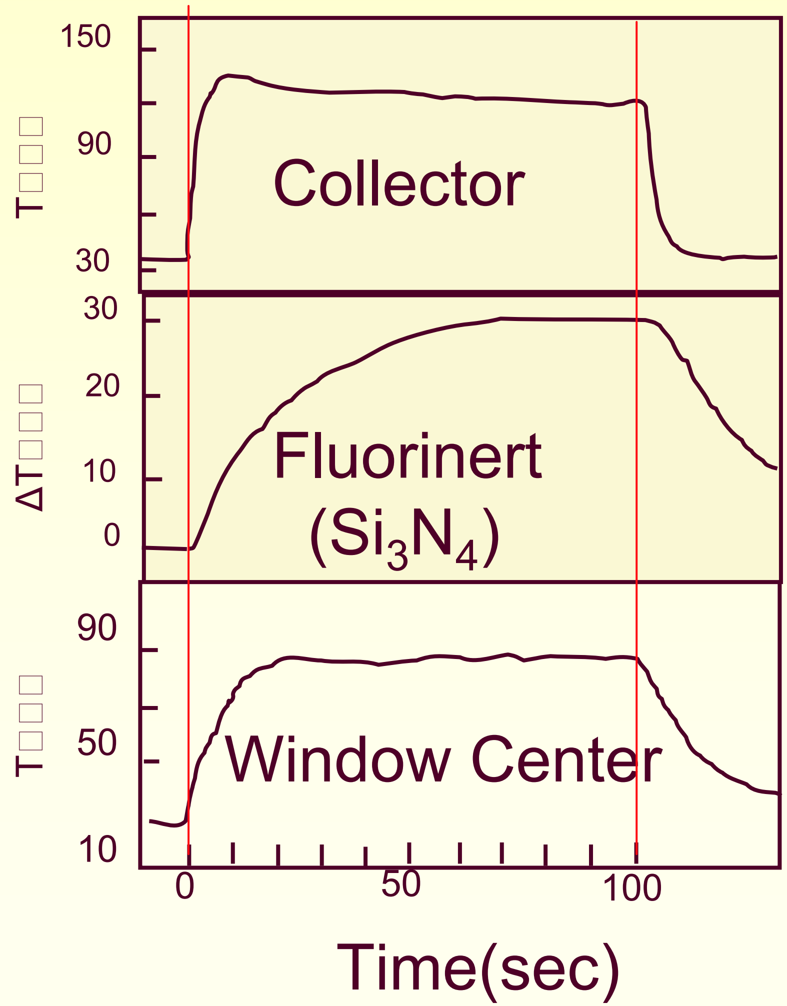
Long pulse operation at 0.5MW (170GHz)

JAERI

Stable Operation of 100sec at ~0.5MW

Good vacuum : <10^{-5} Pa





170-GHz GYROTRON (GYCOM, Russia)

All inner surfaces

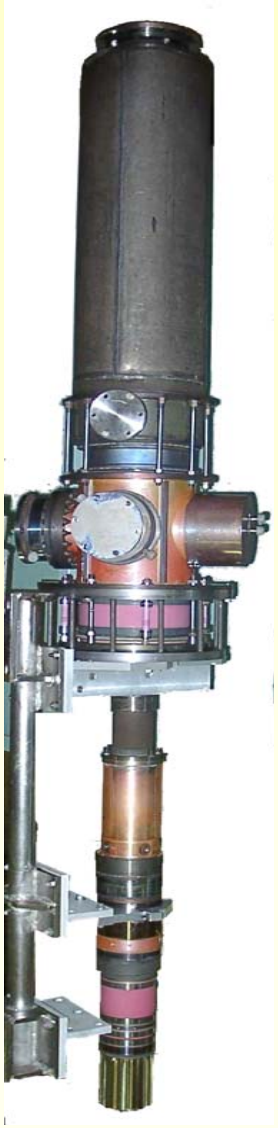
are fabricated of copper and have adequate water cooling for CW operation.

Retarding voltage insulator ∅ 220mm

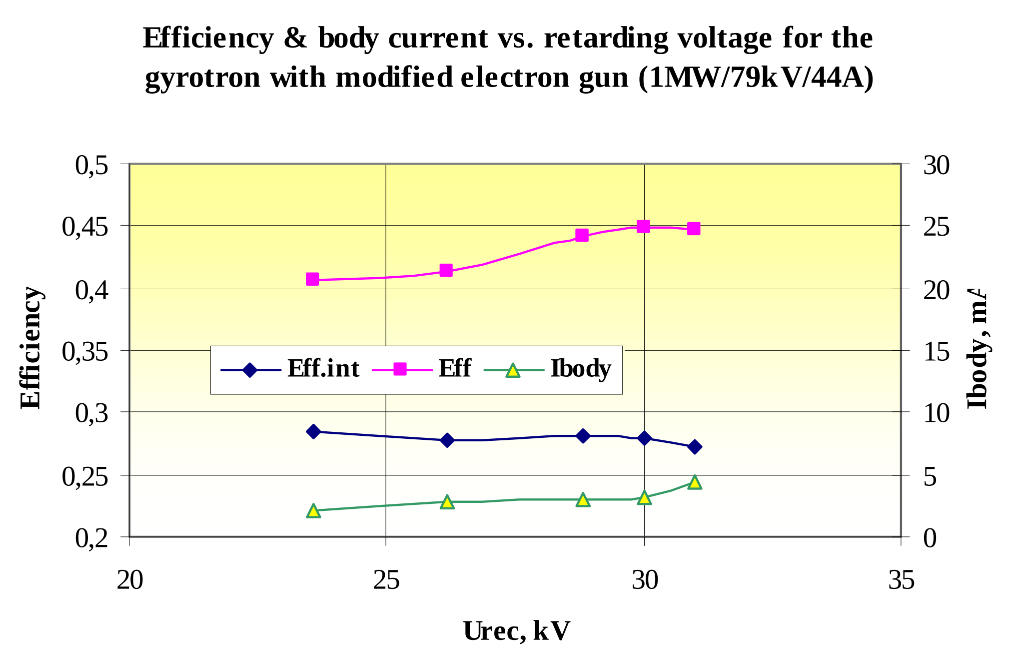
- is provided by flexible cuffs for welding and outside ceramic supports to remove mechanical stress;
- is protected by inner shield to prevent ceramic overheating due to scattered RF rays.

2.7 m; 300 kg; 160 mm magnet bore

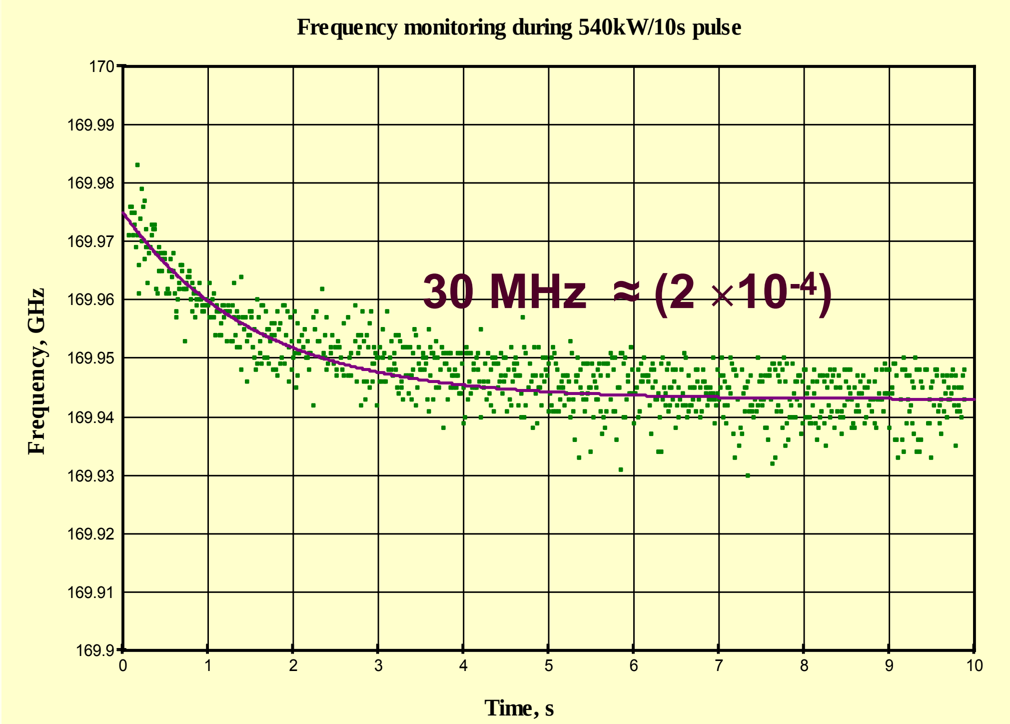
0.5 MW/80 s; 0.7 MW/40 s; 0.85 MW/19 s
45% efficiency



Tests of the 170 GHz gyrotron (GYCOM)



Main parameters of the gyrotron operating in the regime with energy recovery of the electron beam. Small value of the current to the insulated body (< 5 mA) shows a proper operation of the electron gun



Drift of gyrotron frequency due to the thermal expansion of the cavity. Very small relative change of the frequency confirms a proper operation of cavity cooling system.

Next steps in development of conventional gyrotrons for ITER

(in 2004-2005)

Japan team

- Improvement of the mode converter
- Pre-programming control of beam current, magnetic field and cathode-anode voltage

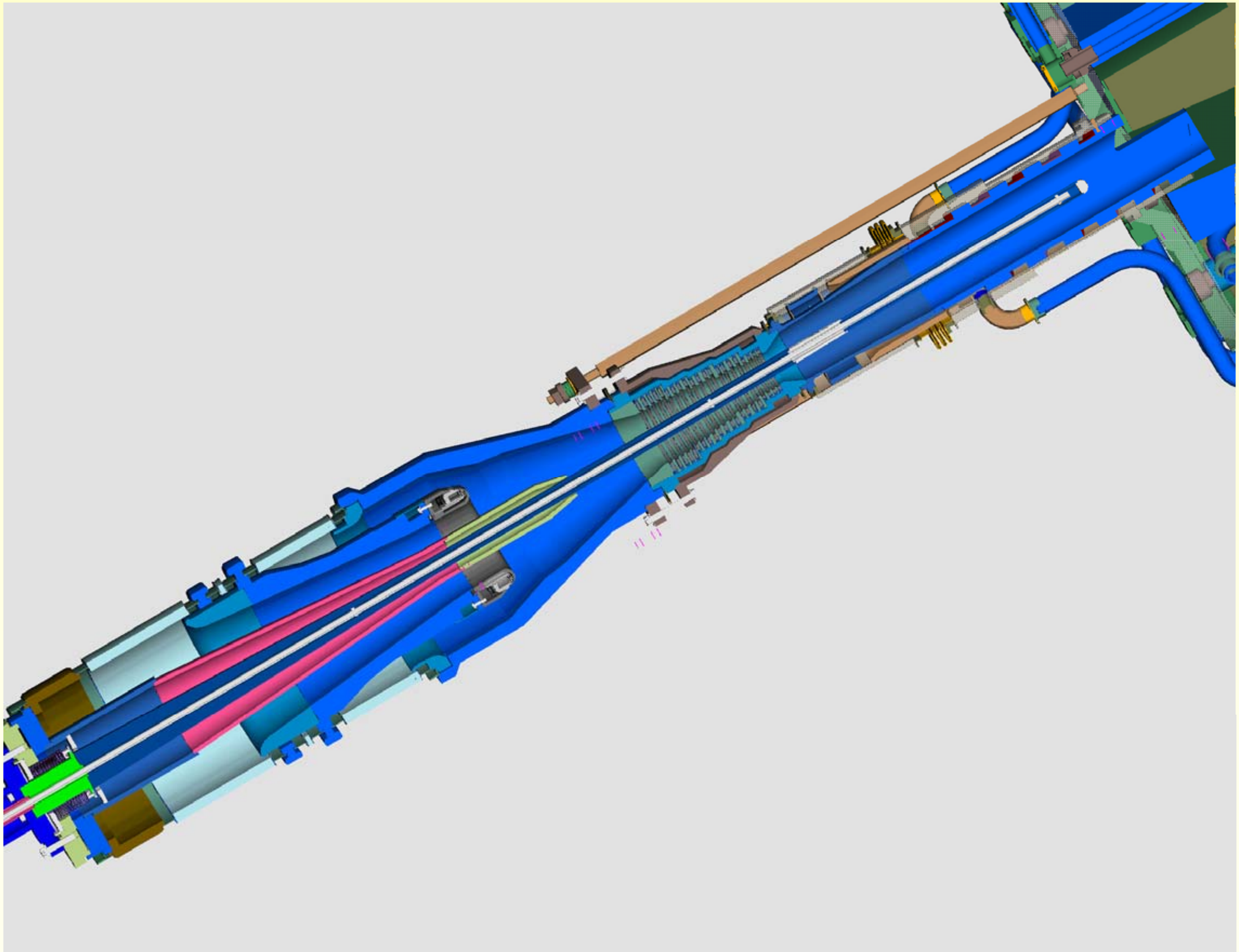
Russia team

- High voltage (85 kV) electron gun => power increase to 1.2 MW
- High-efficiency mode converter => pulse extension

II. Study of advanced gyrotrons concepts

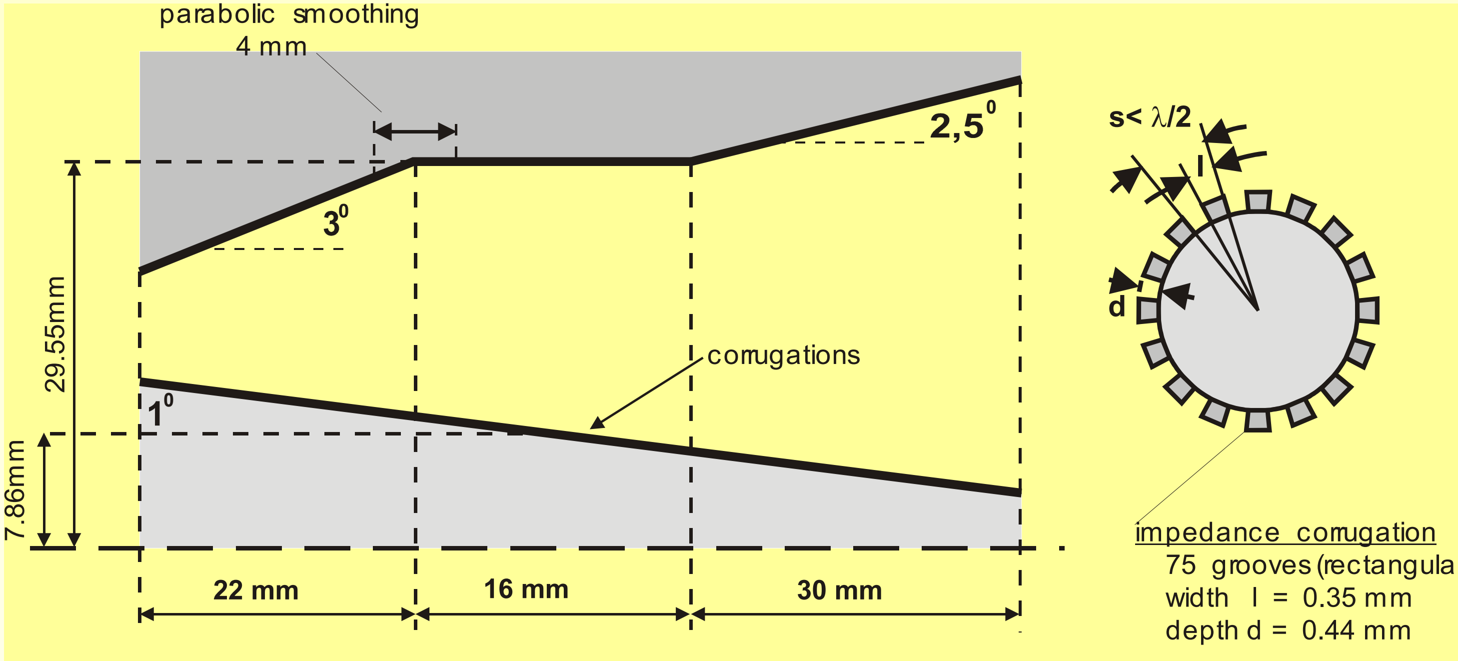
- **1.5-2MW coaxial gyrotron** mainly EU, also Russia
  - increased power per unit
  - power/cost? (much more complicated design)

- **Multi-frequency gyrotron** Russia, EU
  - multi-purpose microwave source



3D cut : Gun – coaxial insert – Beam tunnel – Cavity - Launcher

geometry of the $TE_{34,19}$ coaxial cavity



frequency:	**170 GHz**
Q-value (cold):	**1640**
Q-value (self consistent):	**~2000**
electron beam radius:	**10.0 mm**

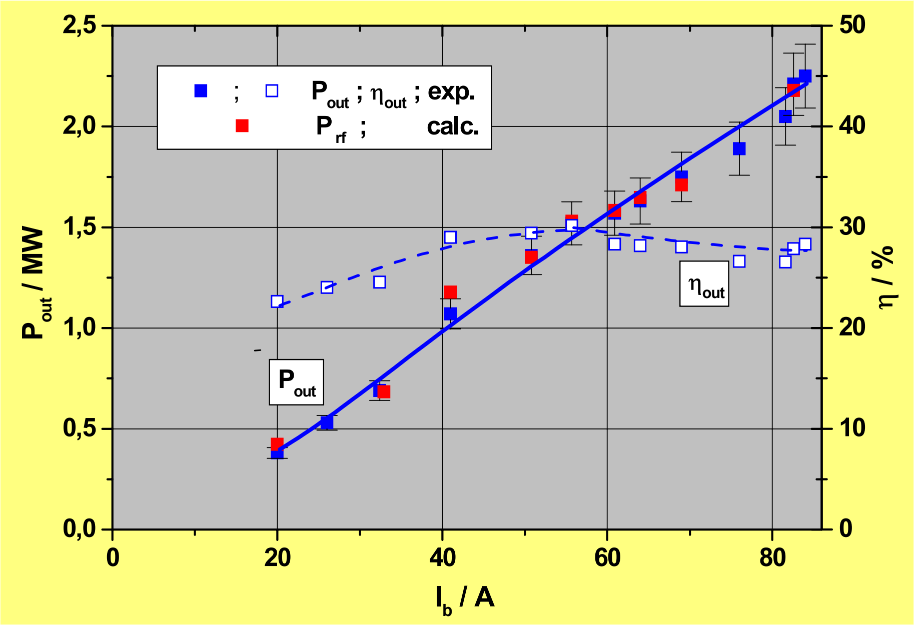
Ohmic losses (ideal copper at 273 K; P_{RF} = 2.2 MW):

peak losses at outer wall	**1 kW/cm²**
peak losses at coaxial insert	**0.06 kW/cm²**
total losses at outer wall	**27 kW**
total losses at the insert	**0.4 kW**

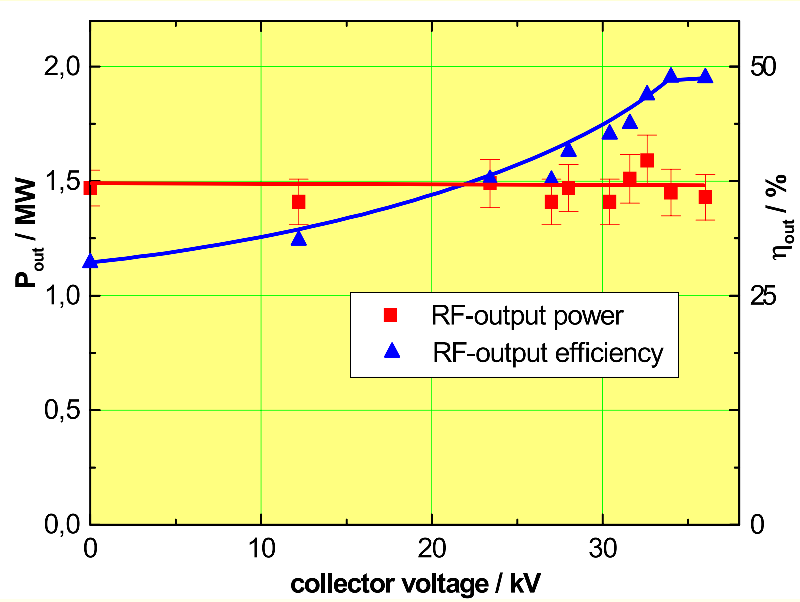
microwave generation

165 GHz

- **RF-output power:** $P_{out} \cong 2.2$ MW with $U_c \cong 94.6$ kV, $I_b \cong 84$ A
- **efficiency (with SDC):** $\eta_{out} \cong 30\ (48)$ % with $U_c \cong 90.4$ kV, $I_b \cong 56$ A at $P_{out} \cong 1.5$ MW



P_{out} vs. I_b



operation with SDC

frame and goal

- based on results obtained in the last years, the manufacturing phase of an industrial prototype of a

2 MW, CW, 170 GHz coaxial cavity gyrotron

started recently in cooperation between European research centres

- FZK Karlsruhe, HUT Helsinki, CRPP Lausanne -
with European tube industry (Thales ED, France)

- delivery of a first prototype is expected for beginning of 2006
- a gyrotron test facility is under preparation at CRPP Lausanne
- the design of main components (electron gun, cavity, quasi optical RF output system) of the 2 MW, CW prototype gyrotron is under verification at short pulse operation at FZK

Frequency tuning in 1 MW gyrotrons

- Series of operating modes

  e.g. $TE_{19.6}$ – $TE_{25.10}$

- Electron gun operating in wide range of magnetic fields

  4.5 - 7 T

- Mode converter for all operating modes

  93-95 %

- E-beam collector operating in varying magnetic field

- Broad band or tunable window

  Brewster / double disk

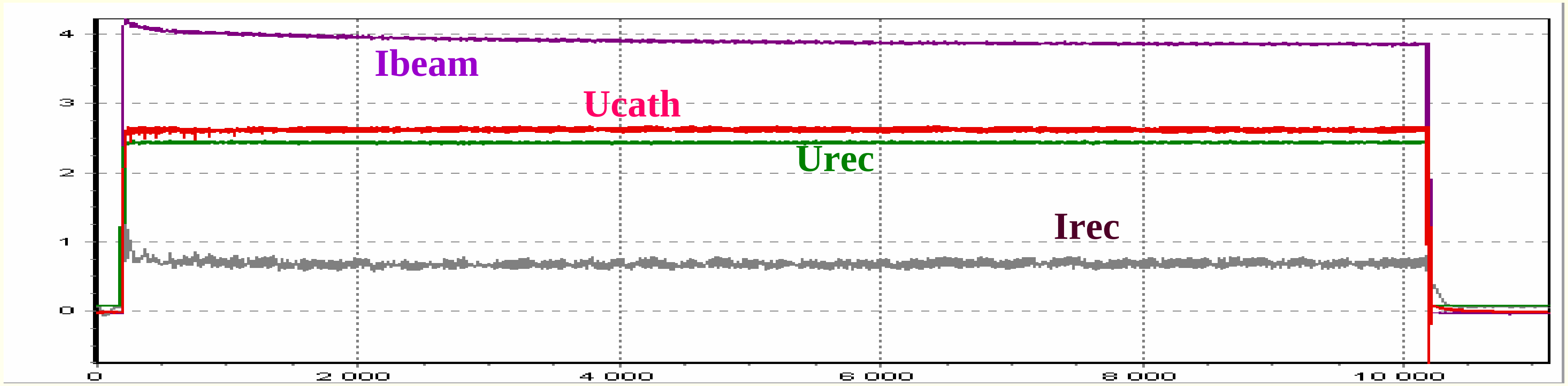
- General design

Two-frequency Industrial Gyrotron (IAP, GYCOM): diamond window, depressed collector

Optimal regimes at varying frequencies

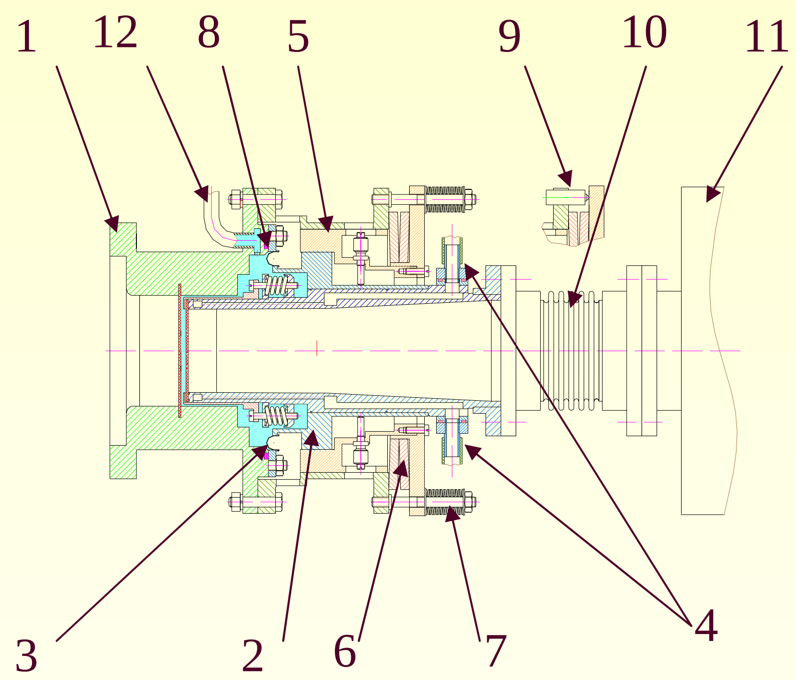
F osc. GHz	Pout kW	Pgauss kW	Ubeam kV	Urec kV	Ibeam A	Int. eff. %	Eff. %
105	672	622	59.5	19	40	28.2	41.5
108	783	692	72.4	22	37.2	29	41.8
140	985	912	76.4	25.6	36.4	35.4	53.3

Gyrotron 140-GHz 10-s pulse. Monitored signals



Double disc output window with fixed adjustable gap: movable unit design

1. Conventional output window with first CVD disc
2. Adjustable unit with second CVD disc
3. Air-vacuum separator cuff
4. Water input/output pipes
5. Stationary unit with guide cylinder
6. Hard disk spring – spacer
7. Set of soft disk springs
8. Gasket
9. Sensors of second disc position
10. Shielding bellows
11. MOU
12. Channel for pumping

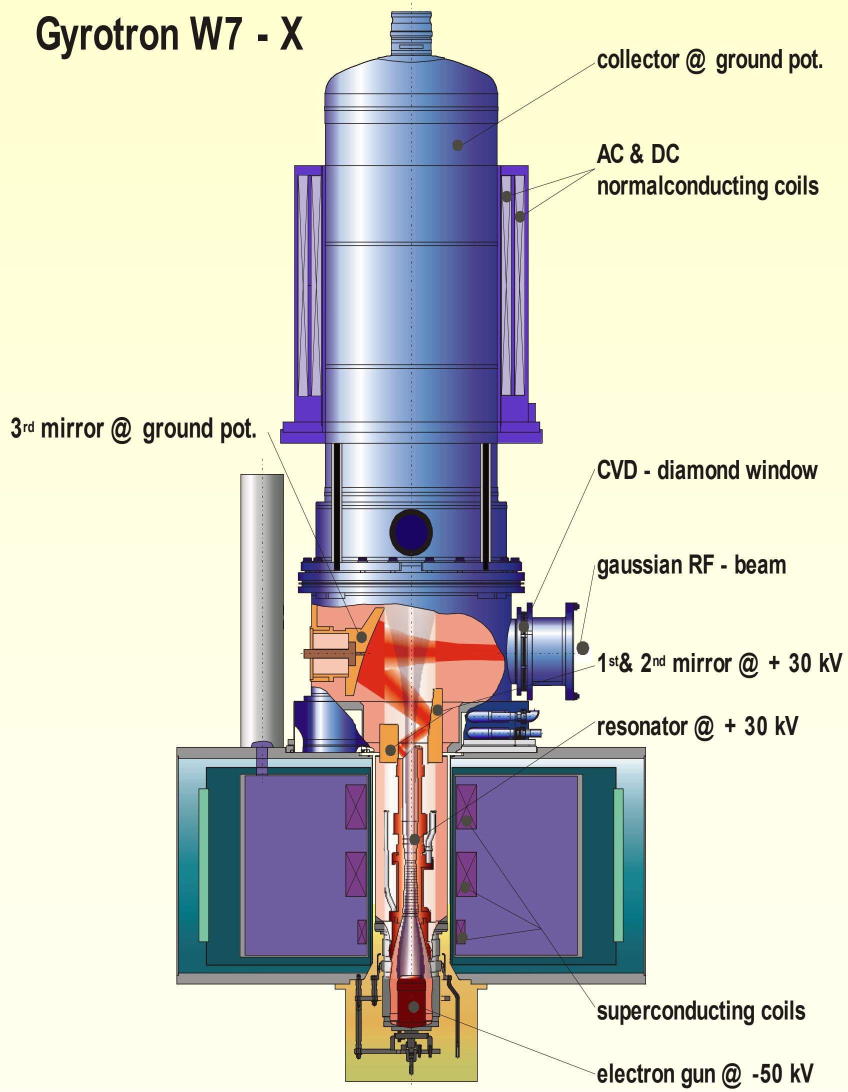


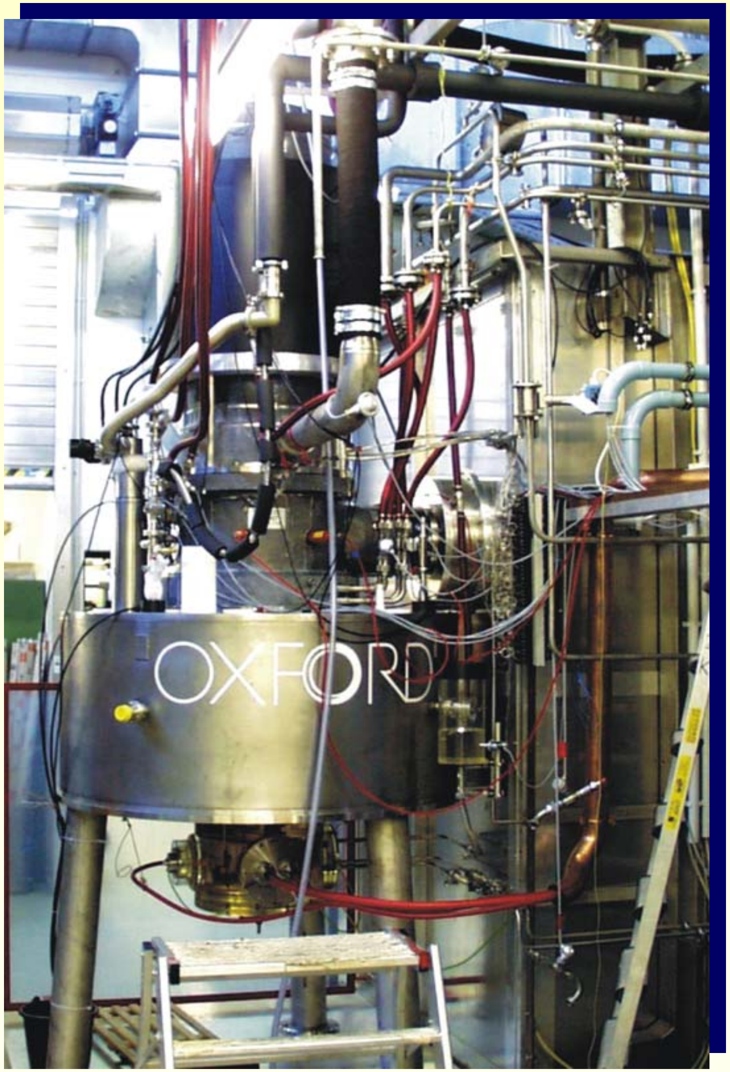
III. Gyrotrons for running and near future installations

Some remarkable results since 2002

Developed for		Developed in
W7-X	140 GHz / 0.9MW / 180 sec 140 GHz / 0.54 MW / 937 sec	EU
JT-60U	110 GHz / 1.2MW/ 4sec	Japan
LHD SST-1	84 GHz / 0.2 MW / 1000sec 82.7 GHz /0.2 MW / 1000sec	Russia

Gyrotron and Testbed





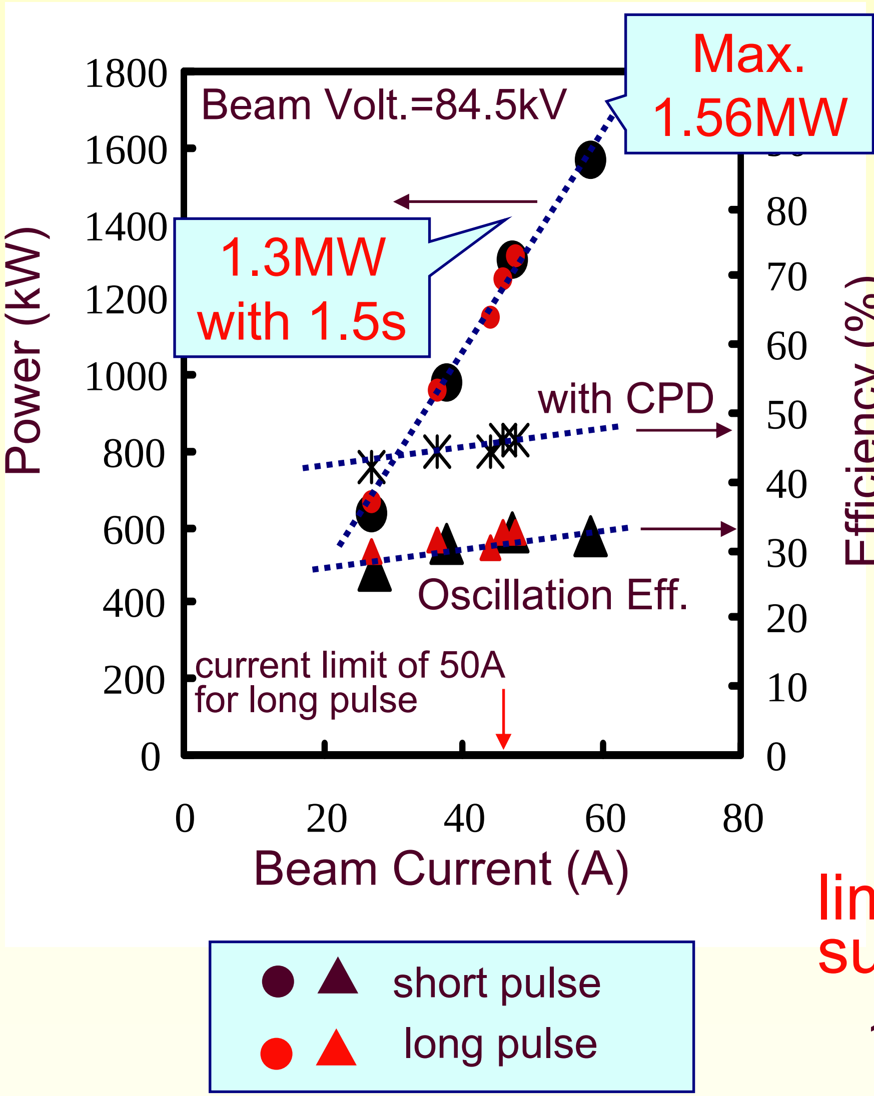
World Record Results of W7-X Prototype Gyrotron

	922 kW; 55 s		892 kW; 180 s	
	efficiency (SDC)	42.2%	efficiency (SDC)	40.9%
	Power / kW	Power / %	Power / kW	Power / %
Generated Power	**972 ± 48**	100	**941 ± 47**	100
Ohmic losses	37 ± 5	3.8	37 ± 5	4.0
Internal Stray Radiation	13 ± 4	1.3	12 ± 4	1.2
Window Losses	0.4	0.04	0.4	0.04
Output Power	**922 ± 46**	95.2	**892 ± 45**	95.0
External Stray Radiaton	16 ± 4	1.7	16 ± 4	1.6
Directed Power	**907 ± 45**	93.5	**876 ± 44**	93.3

Within less than ± 5%: Generated Power + Collector Power = Electrical Input Power

110GHz Gyrotron for JT-60U

JAERI



(1) No difference between short & long pulse operation

(2) No saturation of power with beam current up to 60A

Experimental Results

1.56MW/short pulse

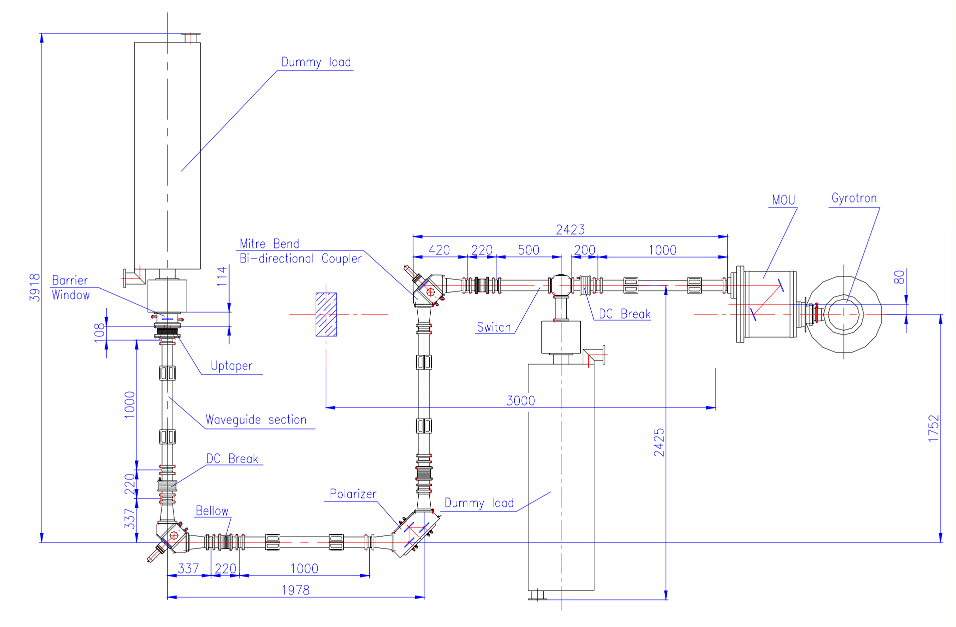
1.3MW/1.5s/46%

limited by capacity of power supply of gyrotron test stand

1MW/5sec, 1.2MW/4sec on JT-60U

IAP RAS GYCOM

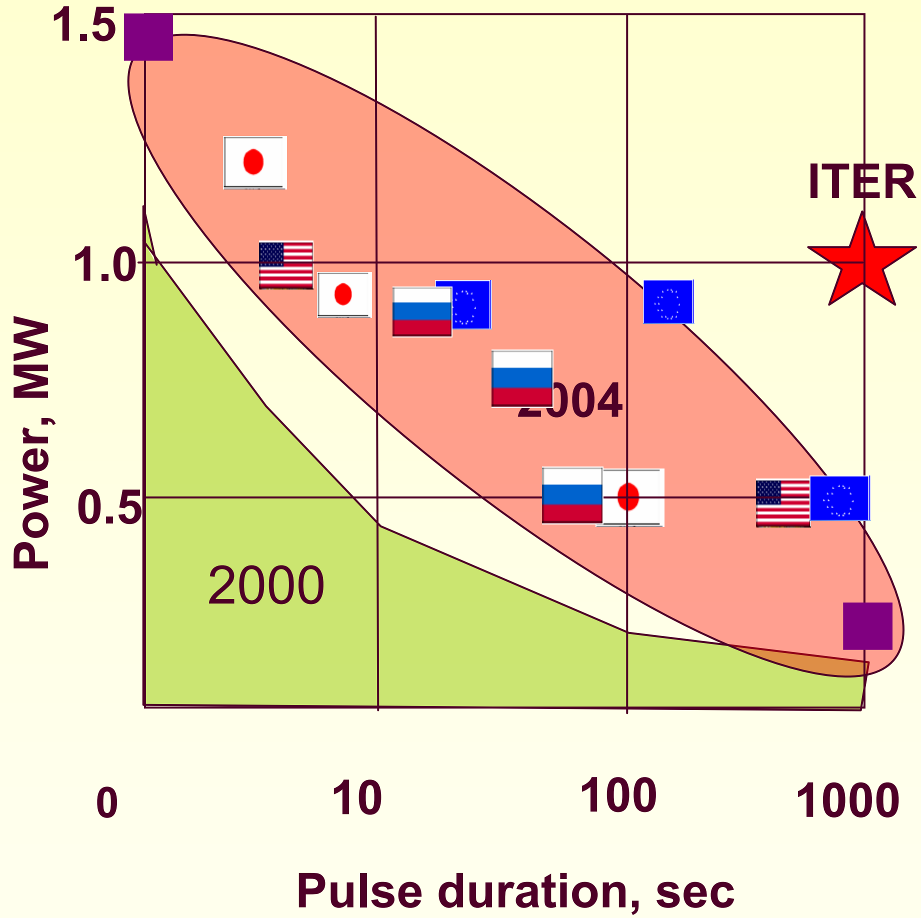
High power test of the 200 kW/CW gyrotron/transmission line system



F = 82.7 GHz , Pgyrotron = 200 kW, Pulse duration: t = 1500 sec.

$P_{\text{Losses MOU}}$ = 11 % , $P_{\text{Losses Tr.Line}}$ = 4 %

Gyrotron performance. Main results since 2000.



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