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Development in Russia of 170 GHz Gyrotron for ITER

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- **Russian gyrotrons for plasma setups**

  ~5 / year. 2009: China-3, Russia-2, Germany, Spain
- **ITER gyrotron parameters and 170GHz/1MW gyrotron design**
- **Test facilities**
- **Long-pulse test of ITER gyrotrons: 09; 10a, 10b;**
- **170 GHz/1.5 MW gyrotron mock-up: Short-pulse test results**
- Multi-frequency gyrotrons
- **Conclusions**

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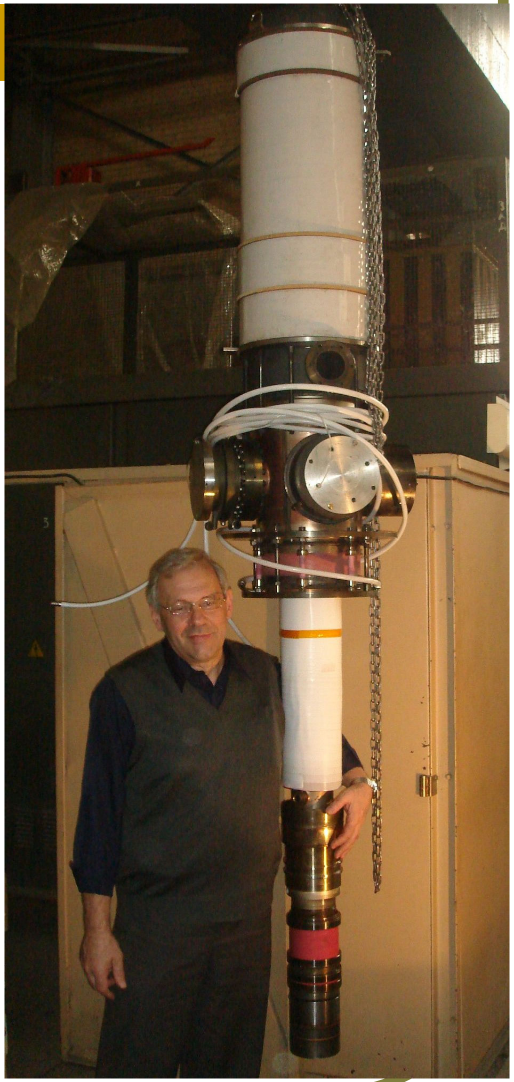
ITER Gyrotron Design / ITER09

- **Depressed-collector** with longitudinal beam sweeping
- **Output windows**:
  - 88(106)-mm CVD diamond main window
  - 123-mm BN relief window
- **Built-in quasi-optical converter** with adjustable last mirror
- **DC break insulator** placed above cryomagnet
- **Cavity** designed for $TE_{25.10.1}$ mode operation
- **Diode type electron gun** designed for current up to 50A
- **All inner surfaces** are fabricated from copper
- and have adequate water cooling for CW operation
- **Magnet bore diameter** 160 mm => gyrotron tube 2.7 m/300 kg

Several modifications of the ITER gyrotron were fabricated and tested (development since 10 years)



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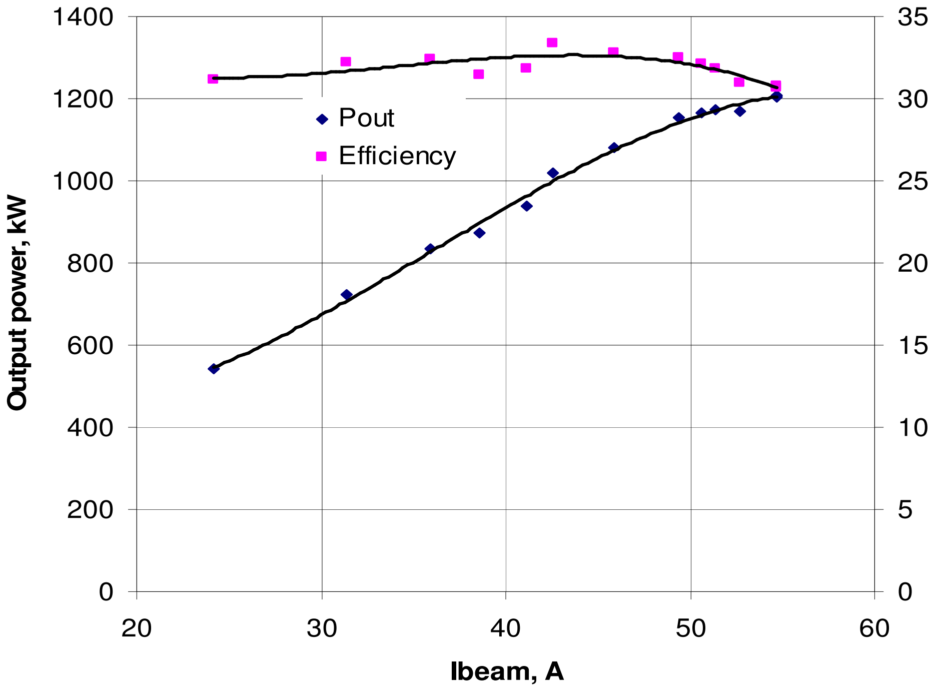
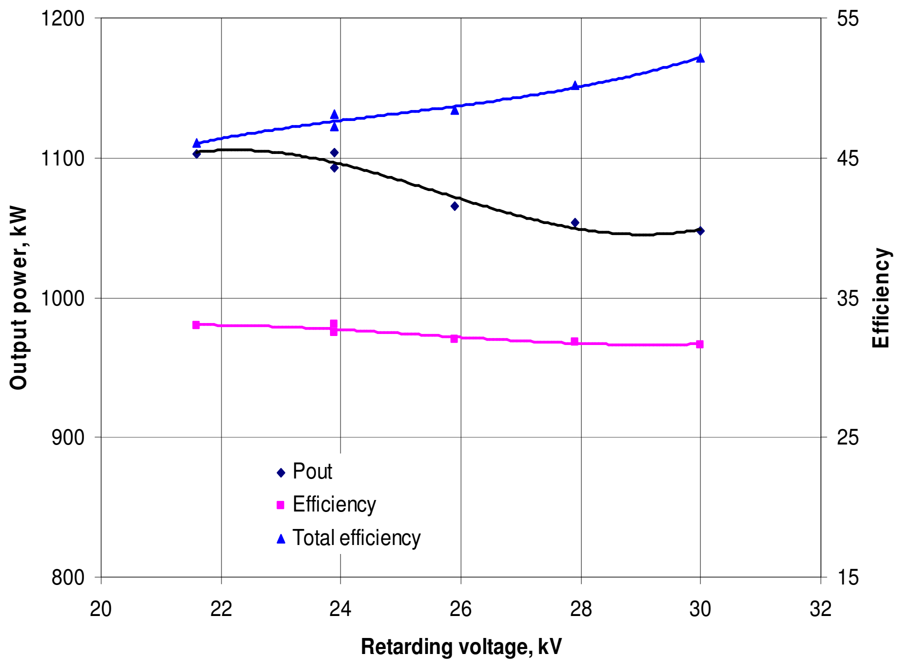
Gyrotron ITER/09

0.1 s-pulse test: Output power & efficiency vs. beam current at beam energy of 76keV

Without energy recovery



With energy recovery, I = 46A

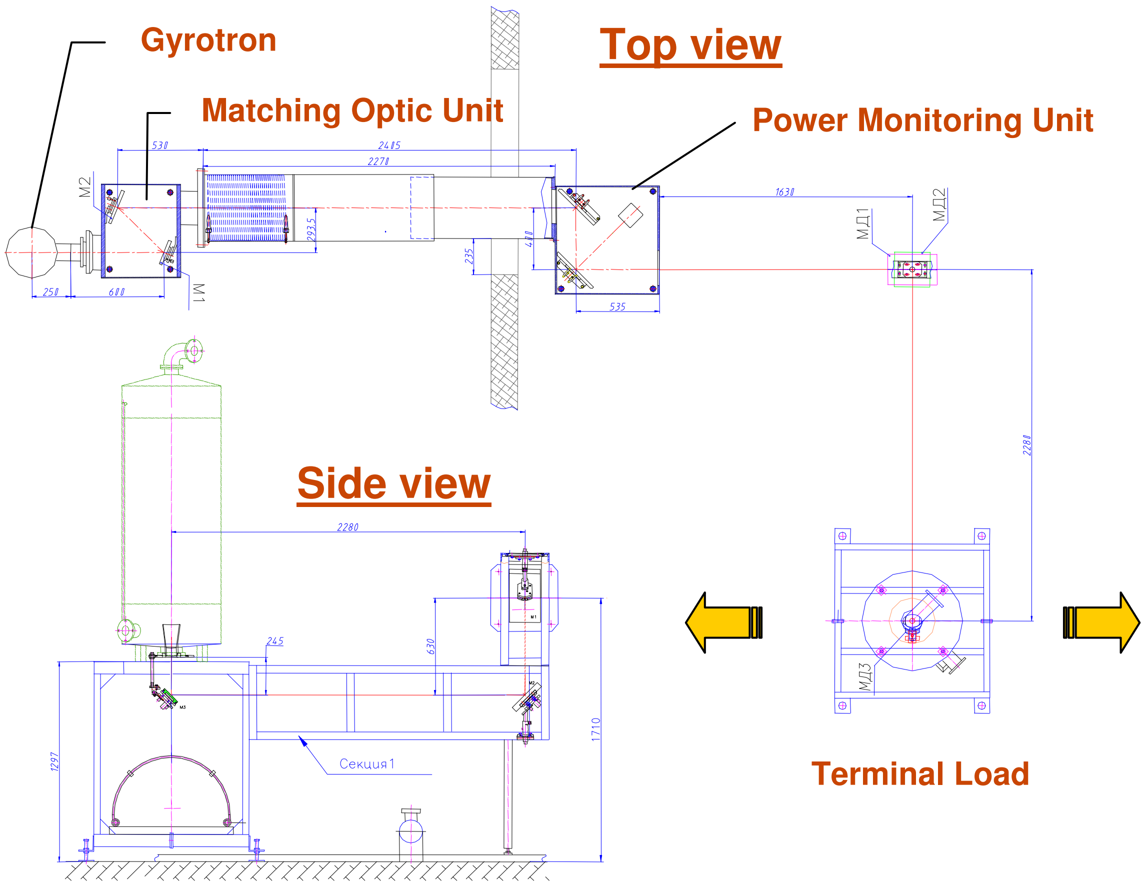


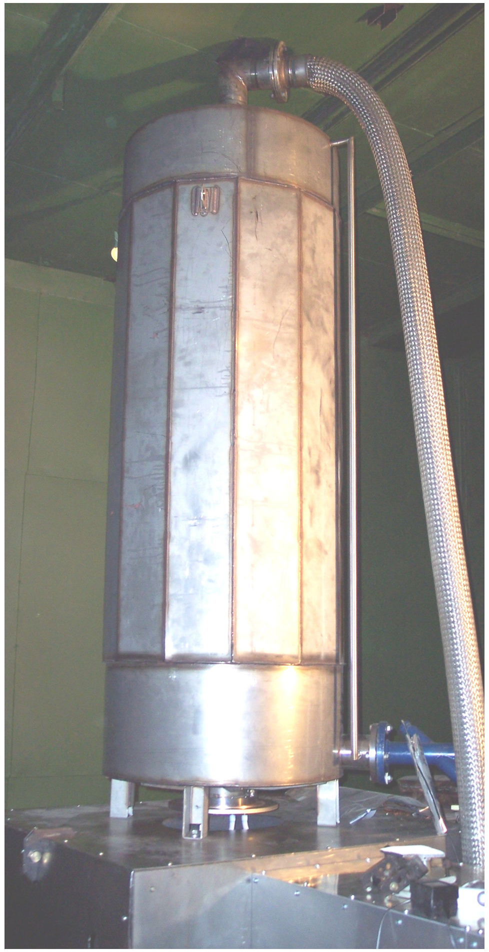
Test facilities: Capability of present and future test facilities

Test facility	Pulse duration	Main power supply voltage/current	Transmission line
Previous Kurchatov Institute	⩽ 300s	⩽ 50kV / ≤ 50A	Mirror transmission line & terminal load at atmospheric pressure
Present Kurchatov Institute*	CW	⩽ 80kV / ≤ 50A	Evacuated waveguide & terminal load
Factory test GYCOM Ltd.**	CW 3 sec	⩽ 70kV / ≤ 24A 90kV / 40 A	Evacuated waveguide & terminal load

* Start of operation – March 2009
** Start of operation - October 2008

Test facilities: Outline of previous test stand at Kurchatov Institute





Previous test stand: Summary of experimental results

Beam voltage kV	Beam current A	Cathode voltage kV	Output power** kW	Total efficiency (CPD) %	Attained pulse length / limitation sec
70.5	25	46	520	~45*	300/ Power supply
76	36	48	830	~48*	203/ Load arcing
76	43	48	1050	~52	116/ MOU arcing

* not optimized
** paraxial part of output radiation

Need modification => done in 2009

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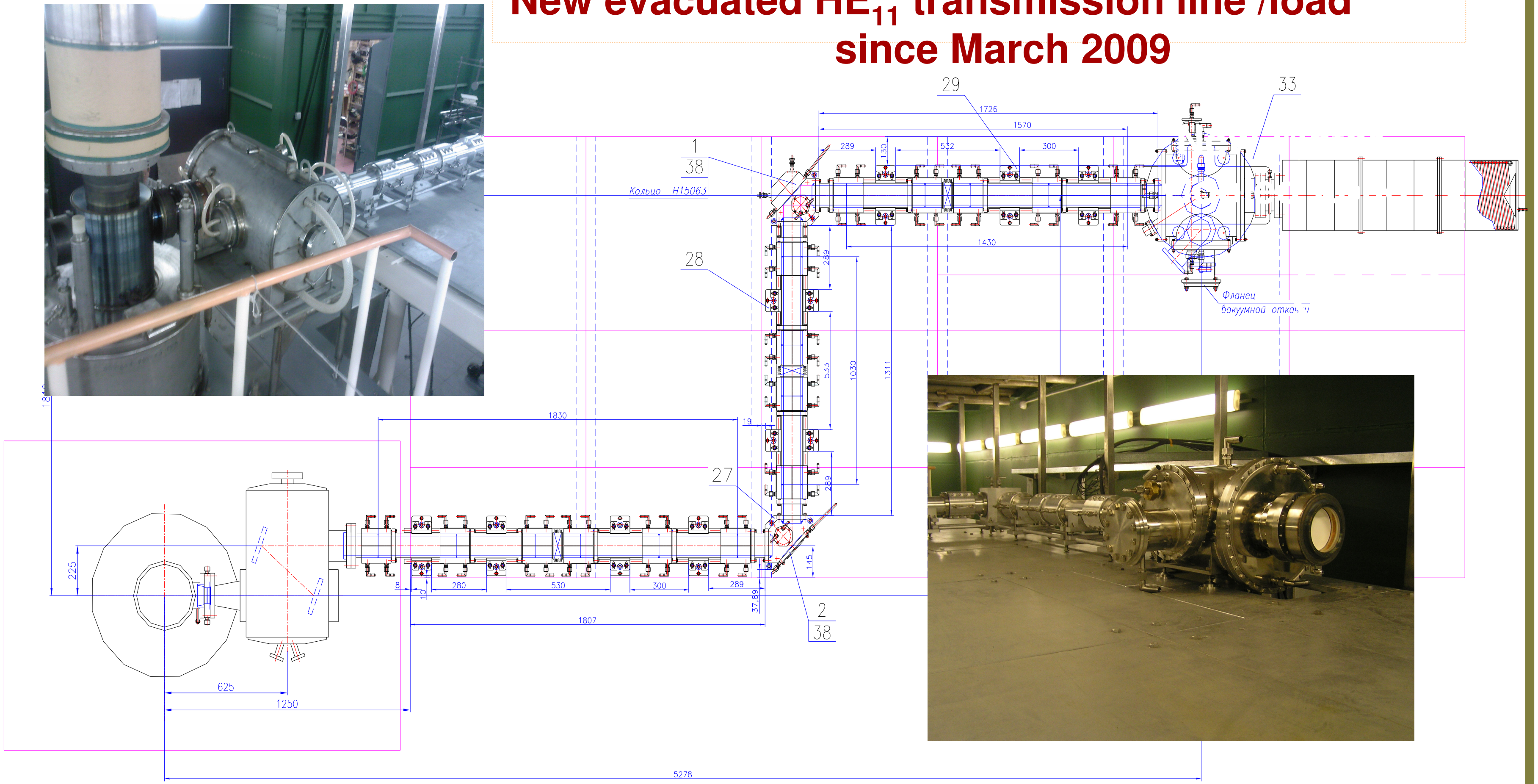
New evacuated HE_{11} transmission line /load since March 2009



First months of new stand use showed very reliable and comfortable operation of the stand (so far 0.65MW/800 sec, 1.05 MW/200 sec)

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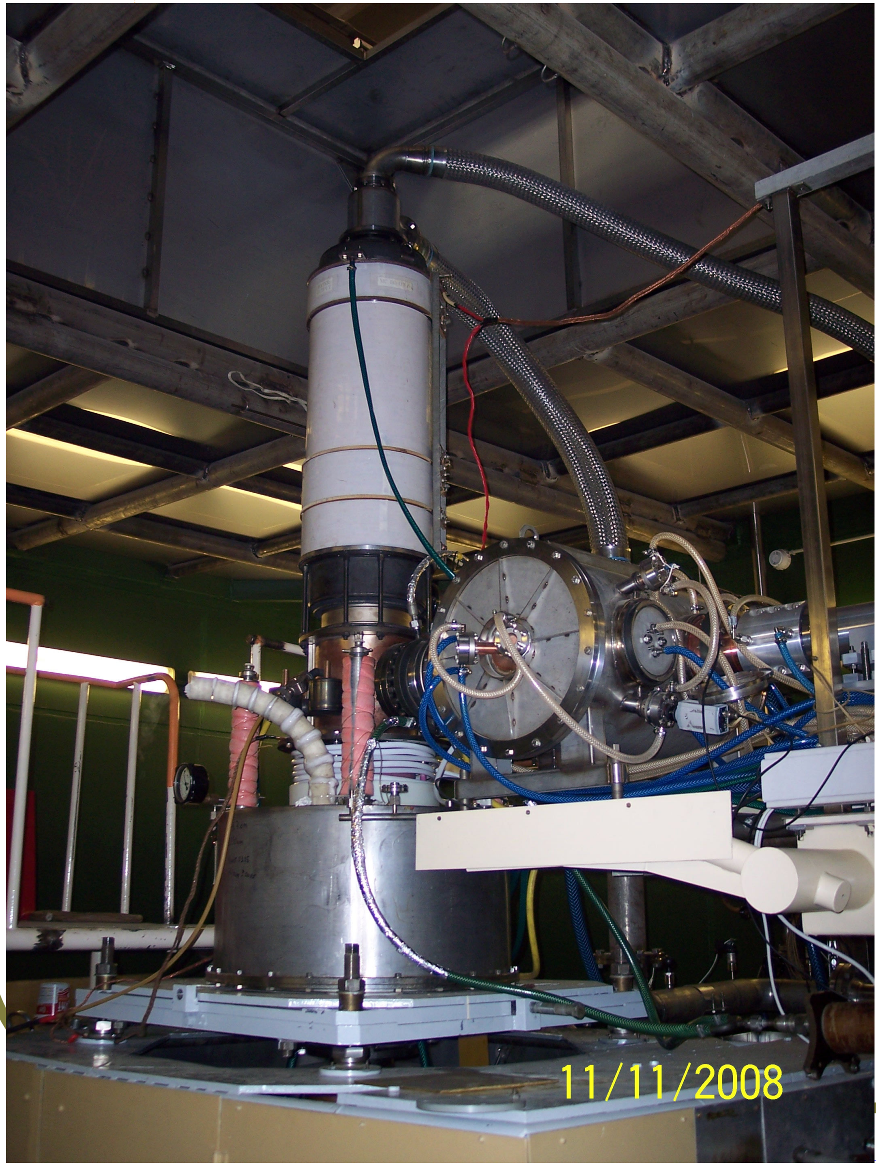
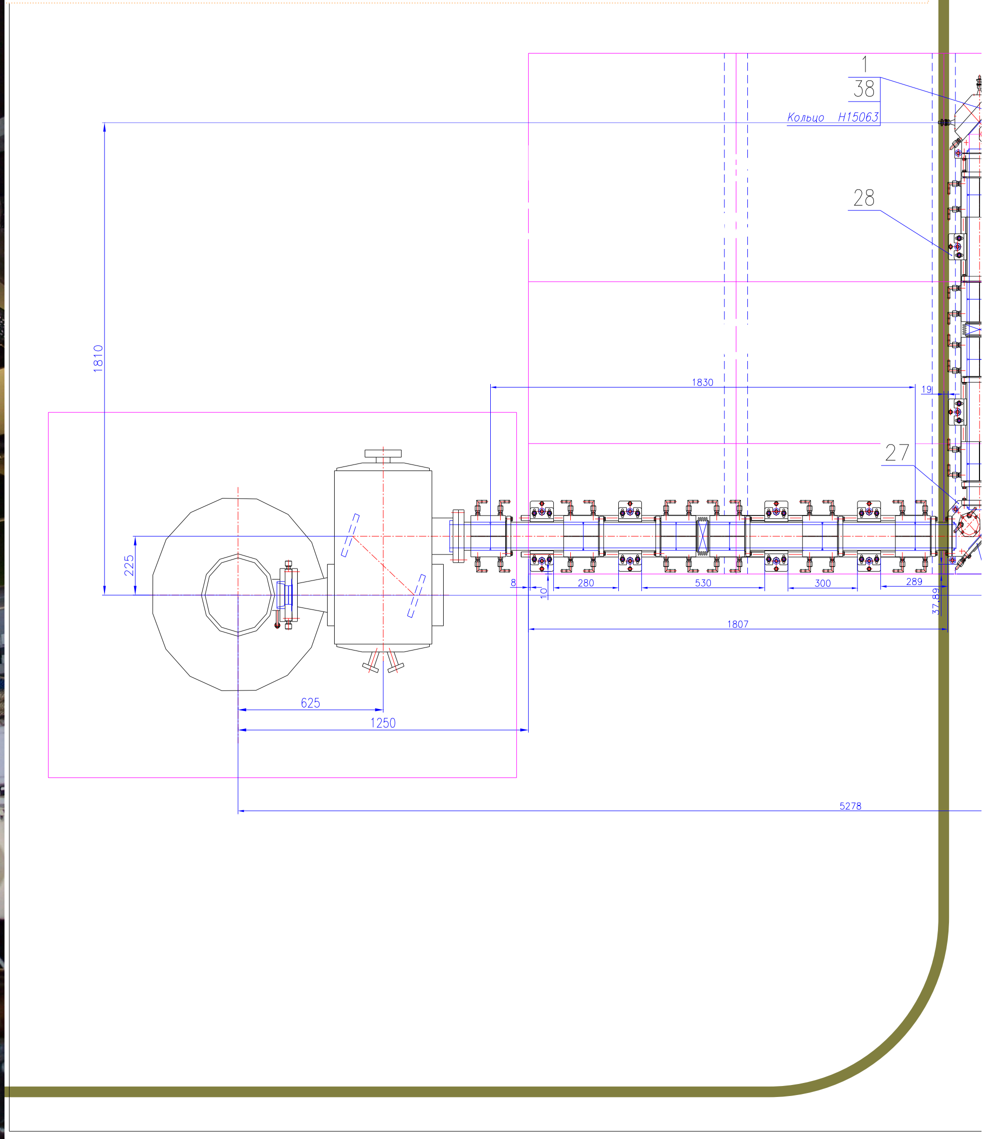
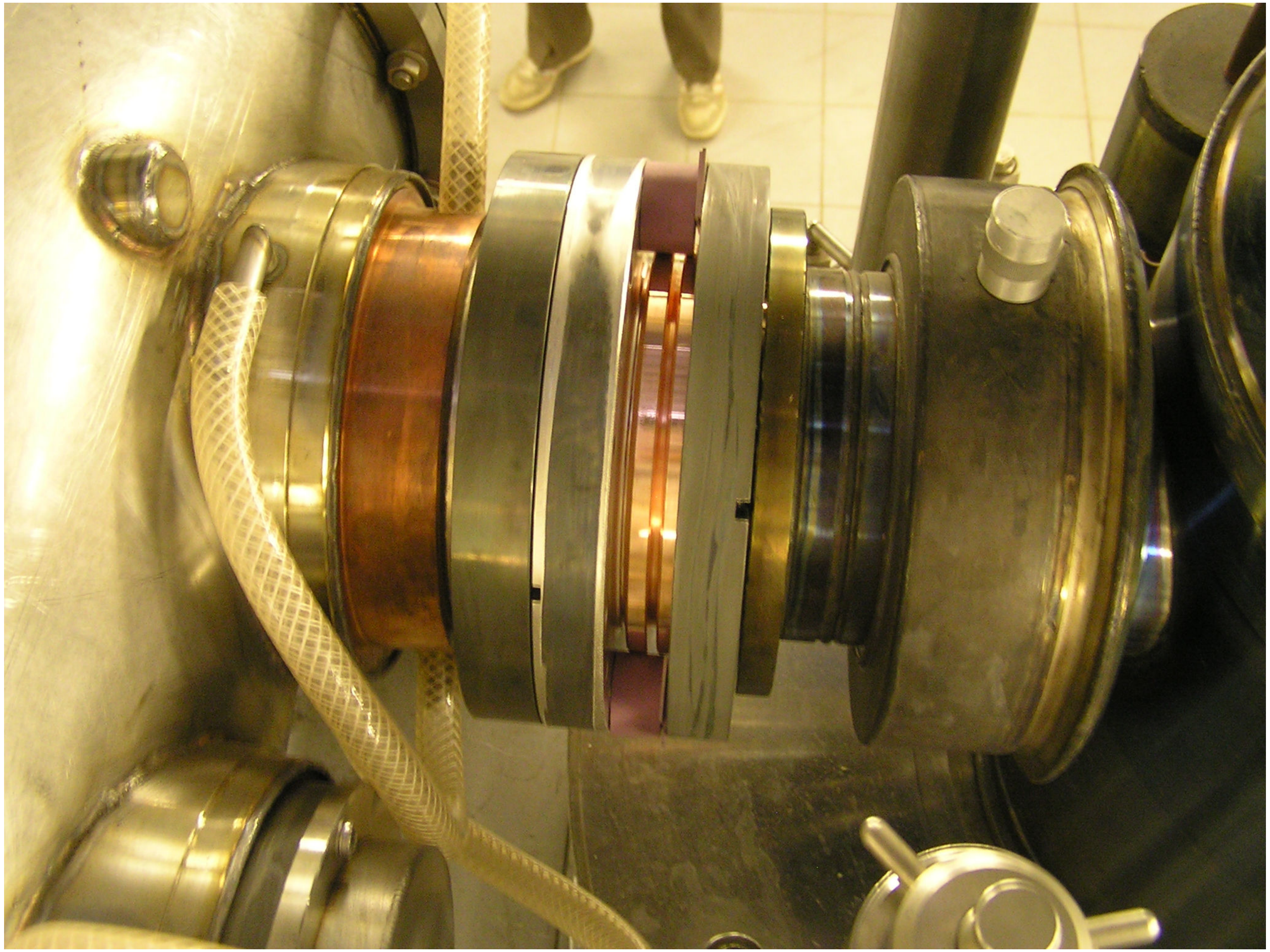
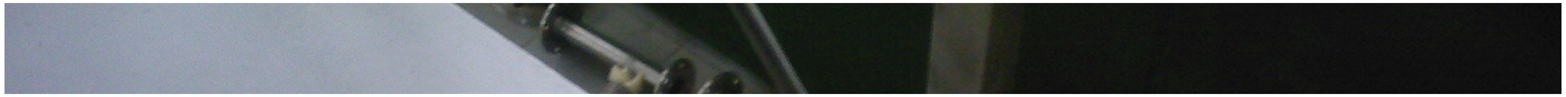
Kurchatov Institute test stand. Evacuated HE_{11} transmission line /load



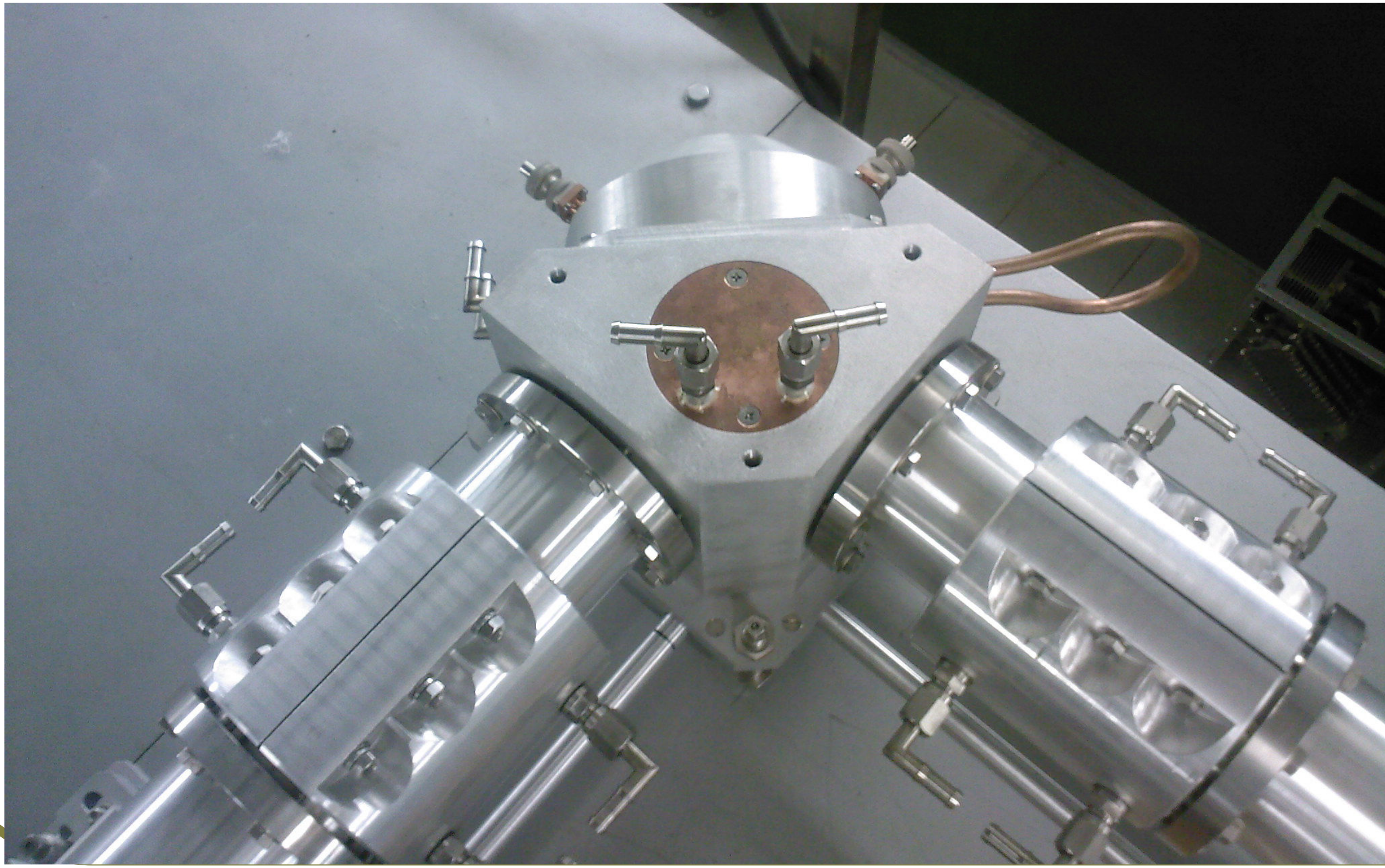


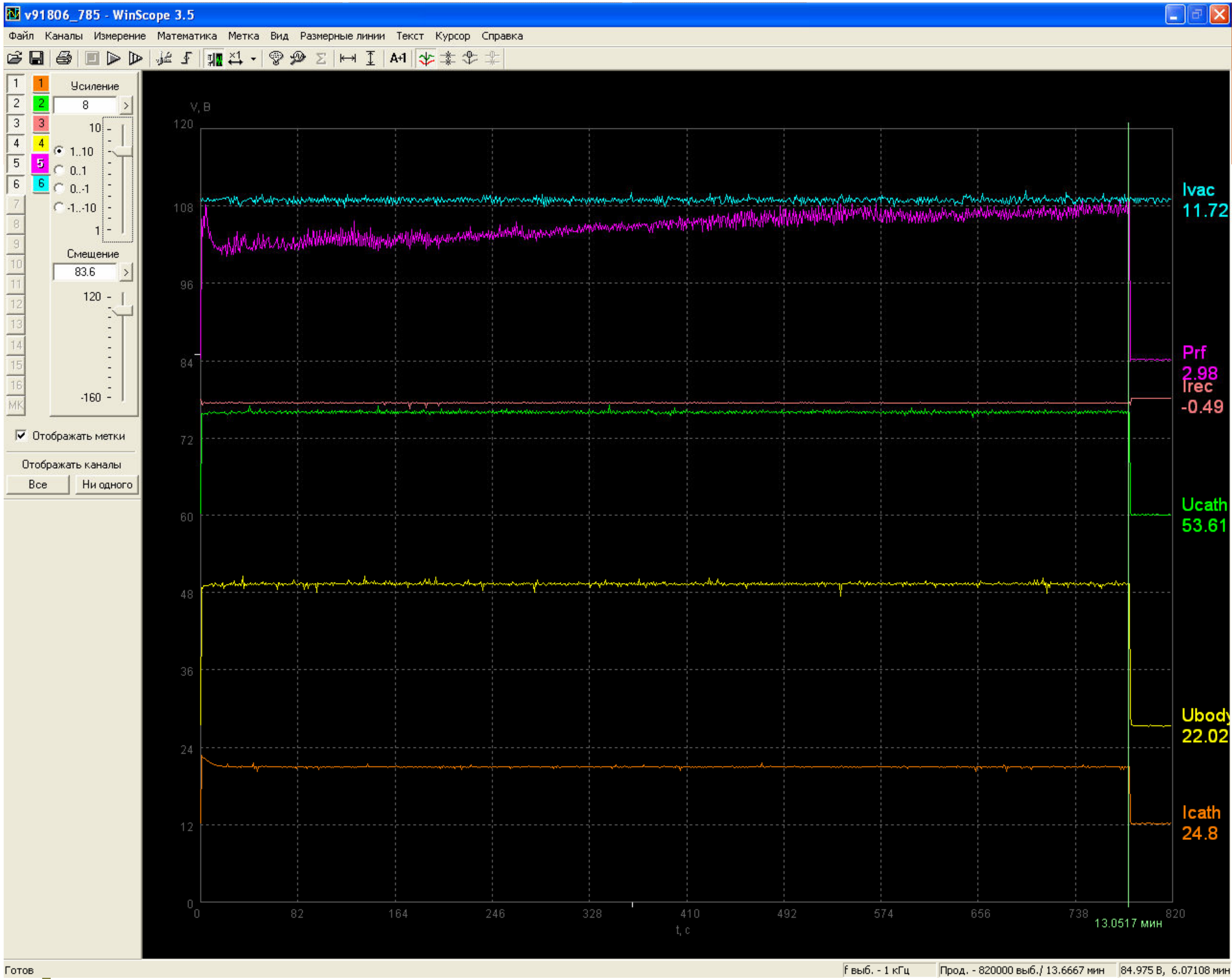
Evacuated transmission line. Gyrotron/MOU flange.





Evacuated transmission line. Miter bend with bi-directional couplers.





Long pulse (0.65 MW/800 sec) test of 170 GHz gyrotron for ITER.
Time traces for voltages, current, vacuum and RF sensors.

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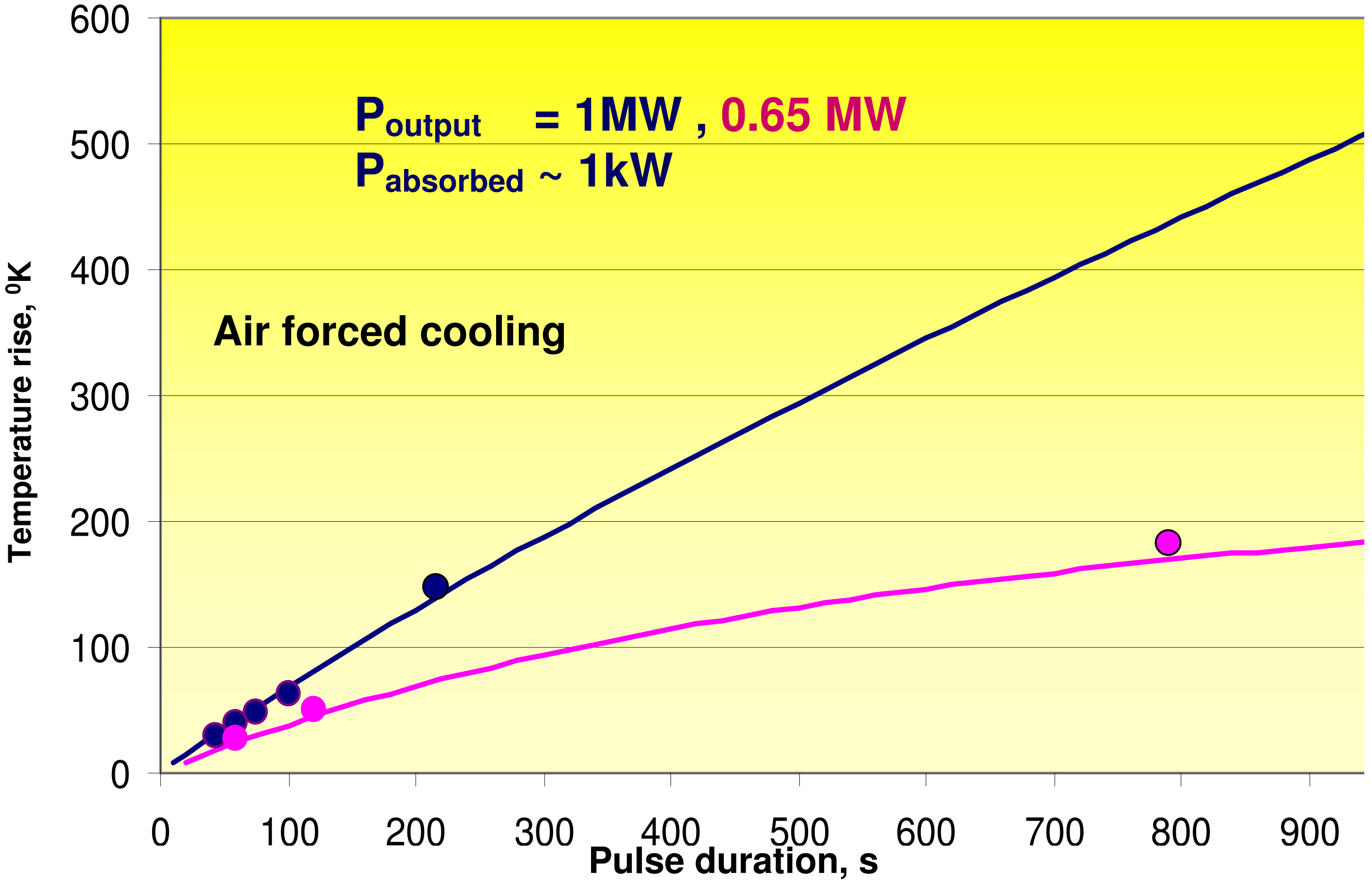
Long-pulse test: Air forced cooling of DC-break ceramic insulator



New cooling system with liquid manufactured. Gyrotron tests – 2009/2010.

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One more stop in 2009:

Window failure due to multiple
pumping out/backing out procedures.
The disc used for 5 years.

Element6 disc,
Culham Al bonding

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New gyrotron ITER10/a

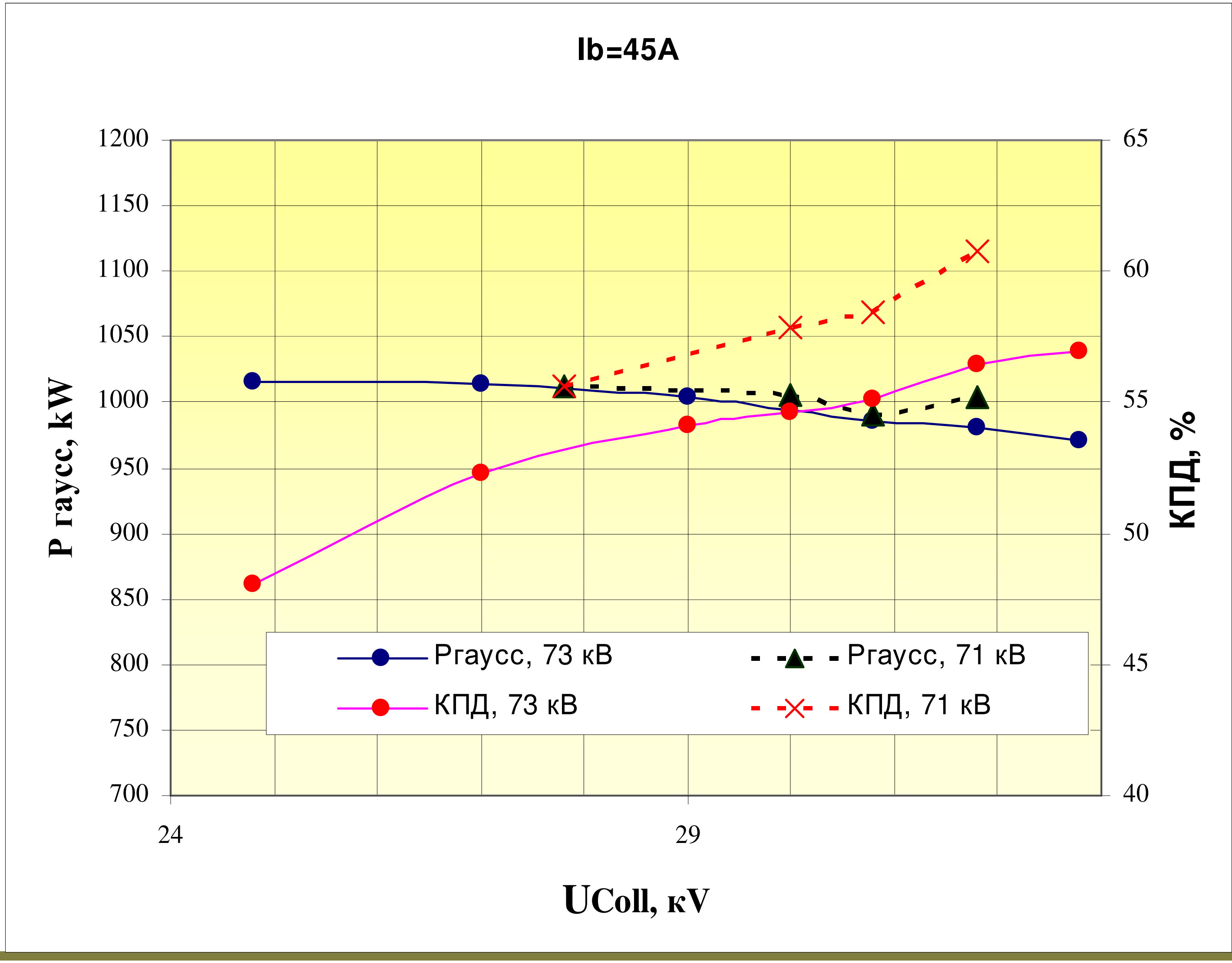
(with a new window
and liquid insulator cooling)

in the test bench.

Tests restart – March 2010

LHe-free magnet is used
(Cryomagnetics Inc., USA).

Gyrotron ITER 10a. Power measured at 300 mm from the window (0.1 sec)



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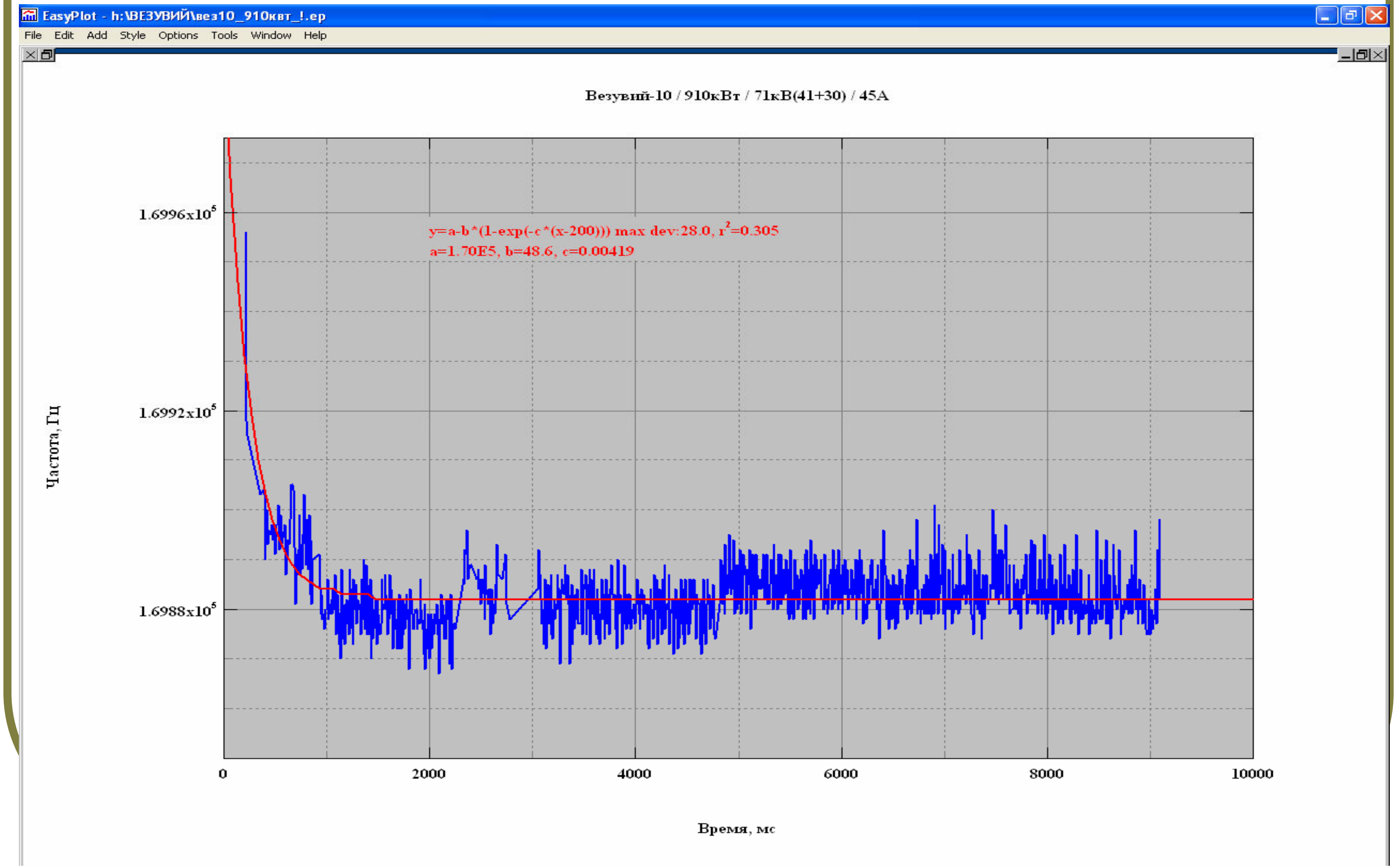
Gyrotron ITER/10a. Frequency drift in 9 sec pulse



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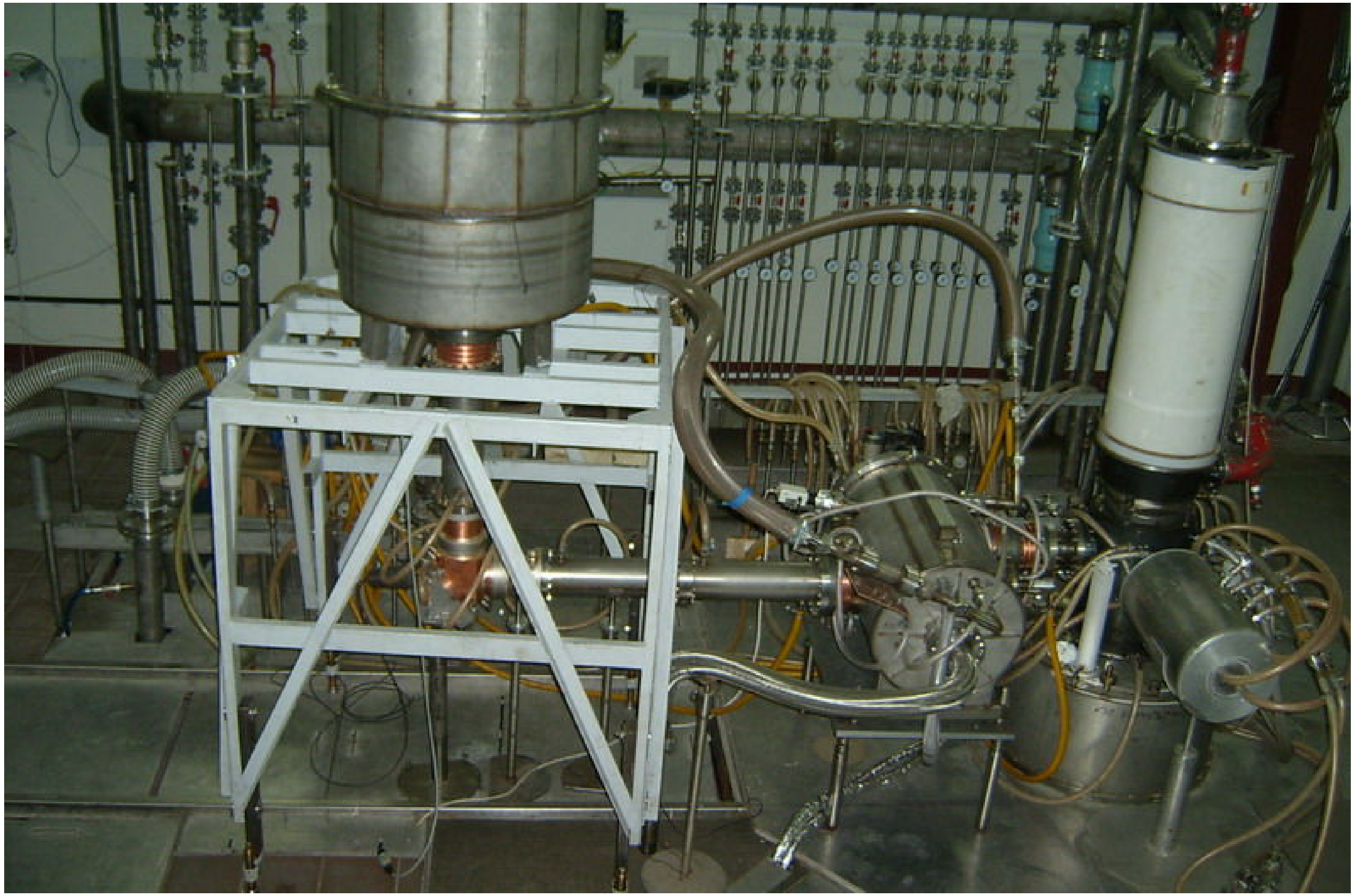
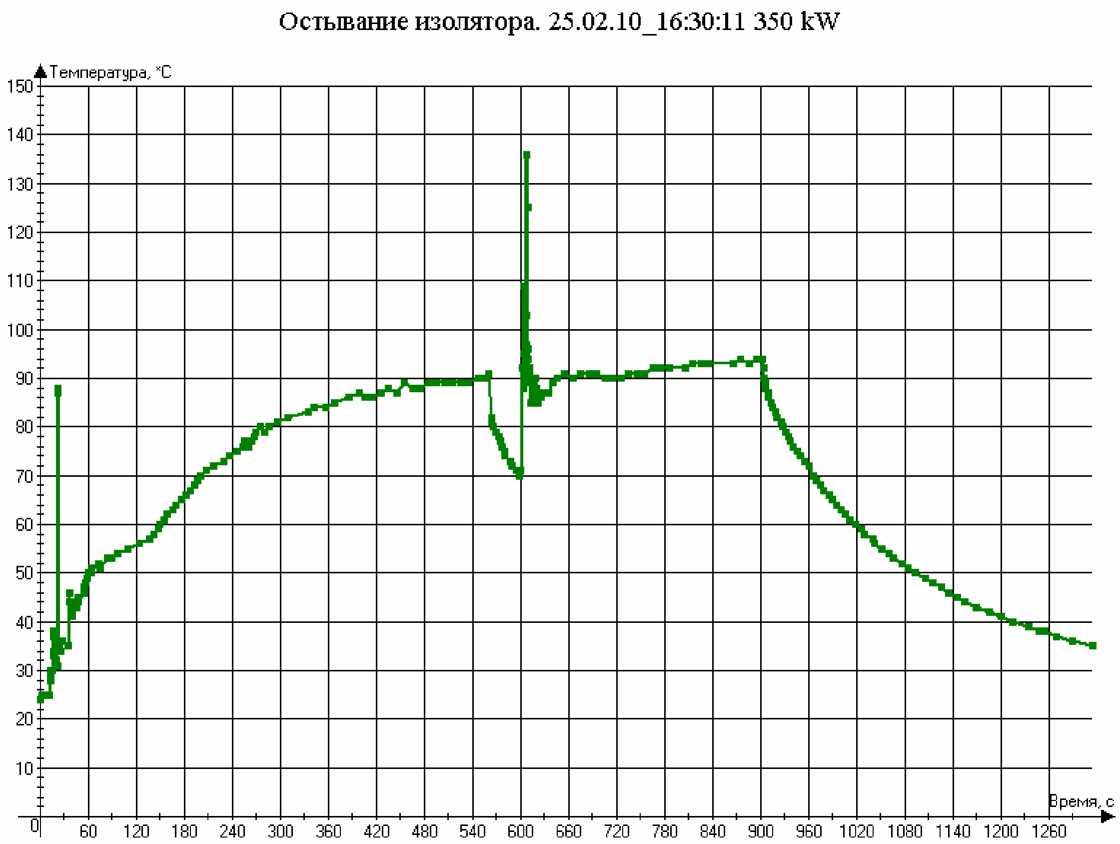
Gyrotron ITER/10b in the test bench at Nizhny Novgorod



Series 6 pulses 400 kW/ 300 sec+300sec pause/ 45+25 kV/18 A/50%/ 7ma.

Gyrotron ITER/10b. Ceramics temperature – air cooling.



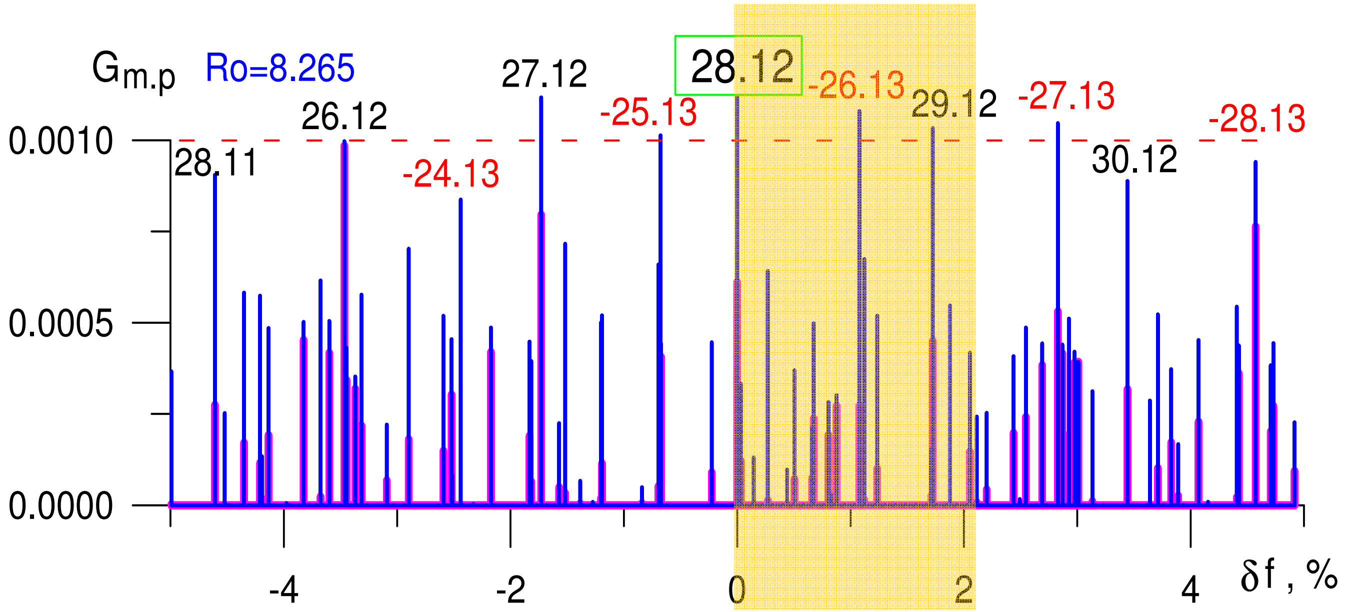
Tasks for 2010

- Demonstrate 1 MW/1000 sec operation
- Study power modulation
- Reliability tests

170 GHz/1.5 MW gyrotron: Design parameters

Frequency	170 GHz
Nominal RF Power	1.5 MW
RF Output Efficiency	> 45 %
Accelerating Voltage	95 - 100 kV
Depression Voltage	35-40 kV
Beam Current	50 - 60 A
Cavity	cylindrical $TE_{28.12}$
Cavity magnetic field	< 7 T
Pulse duration	1000 s
Depressed Collector	single stage
Window	Diamond (CVD)
Output radiation	TEM_{00} Gaussian

Some features of $TE_{28.12}$ gyrotron

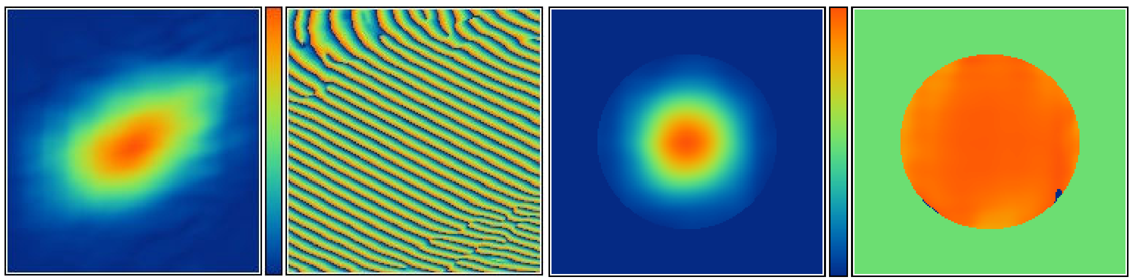


Electron beam – mode coupling coefficients

Cathode

Launcher Gaussian mode content – 98.3%

RF Window Gaussian mode content – 99 %



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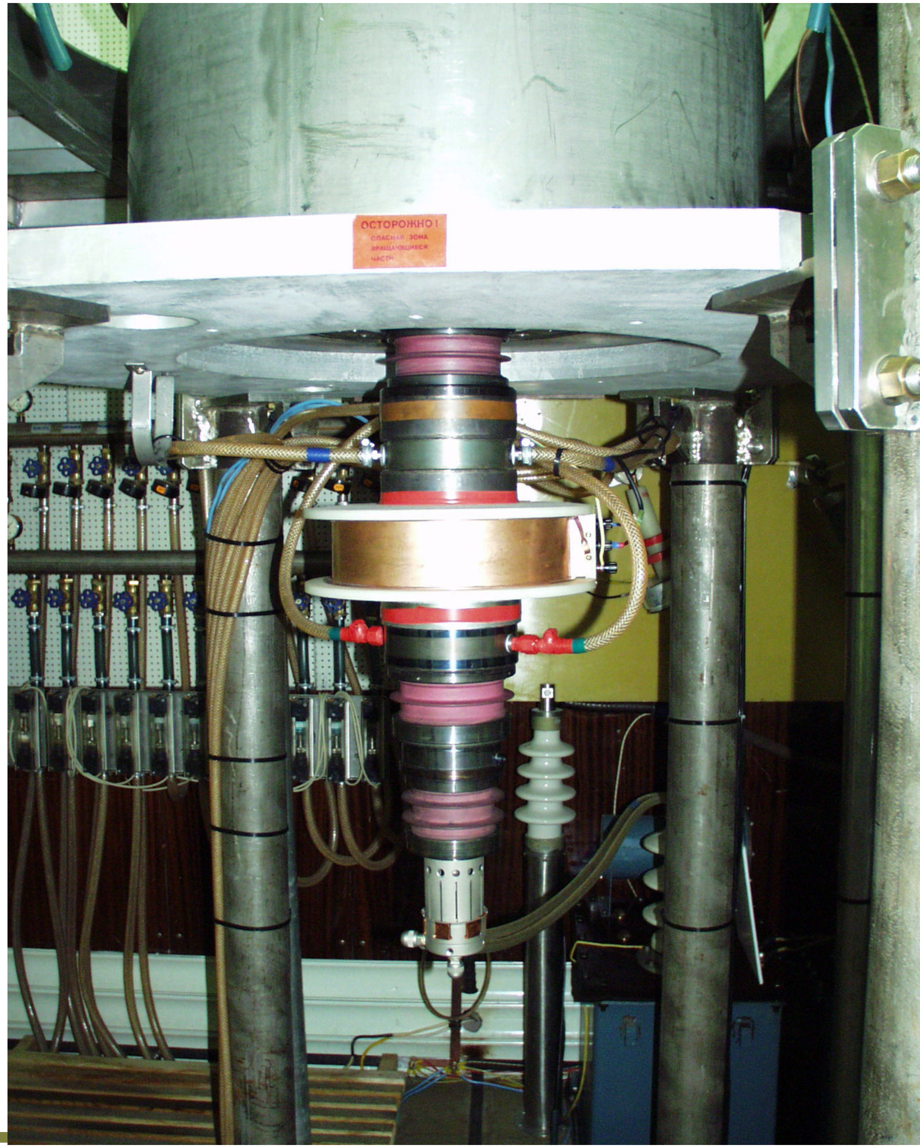

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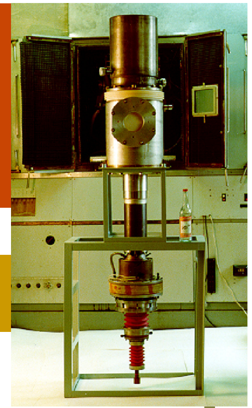
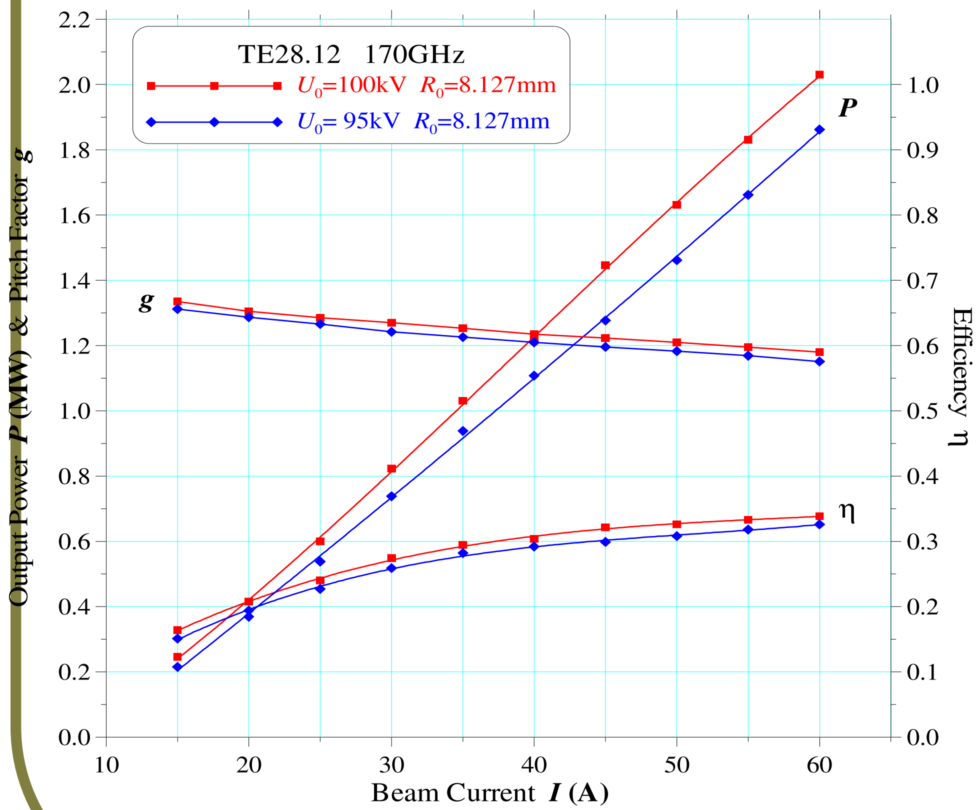
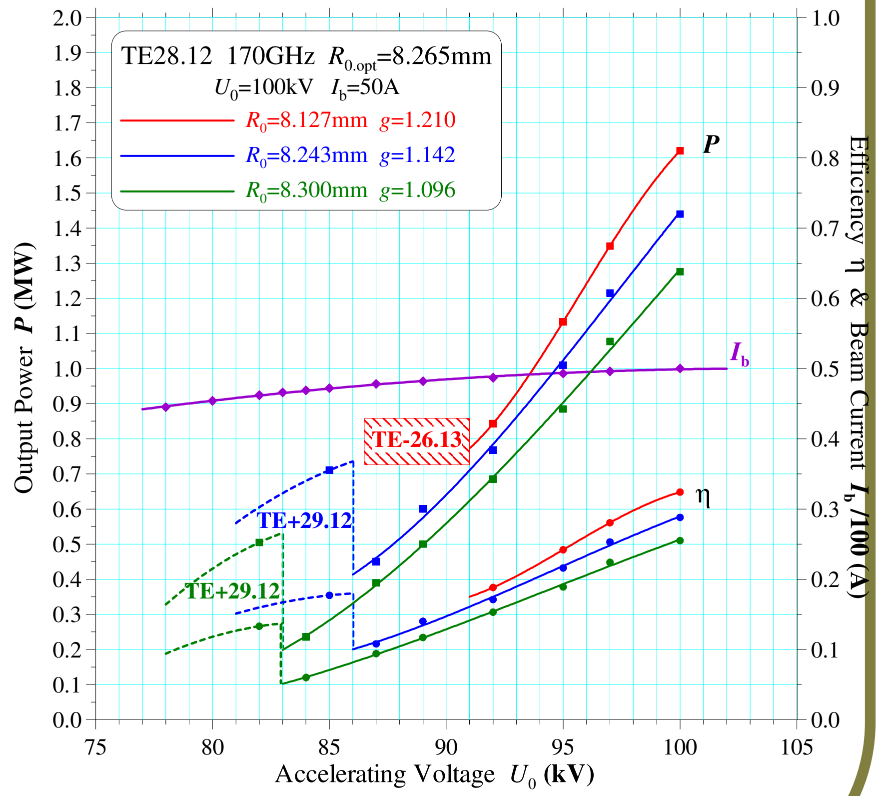


170 GHz/1.5 MW gyrotron: 50-100 μsec-pulse test results





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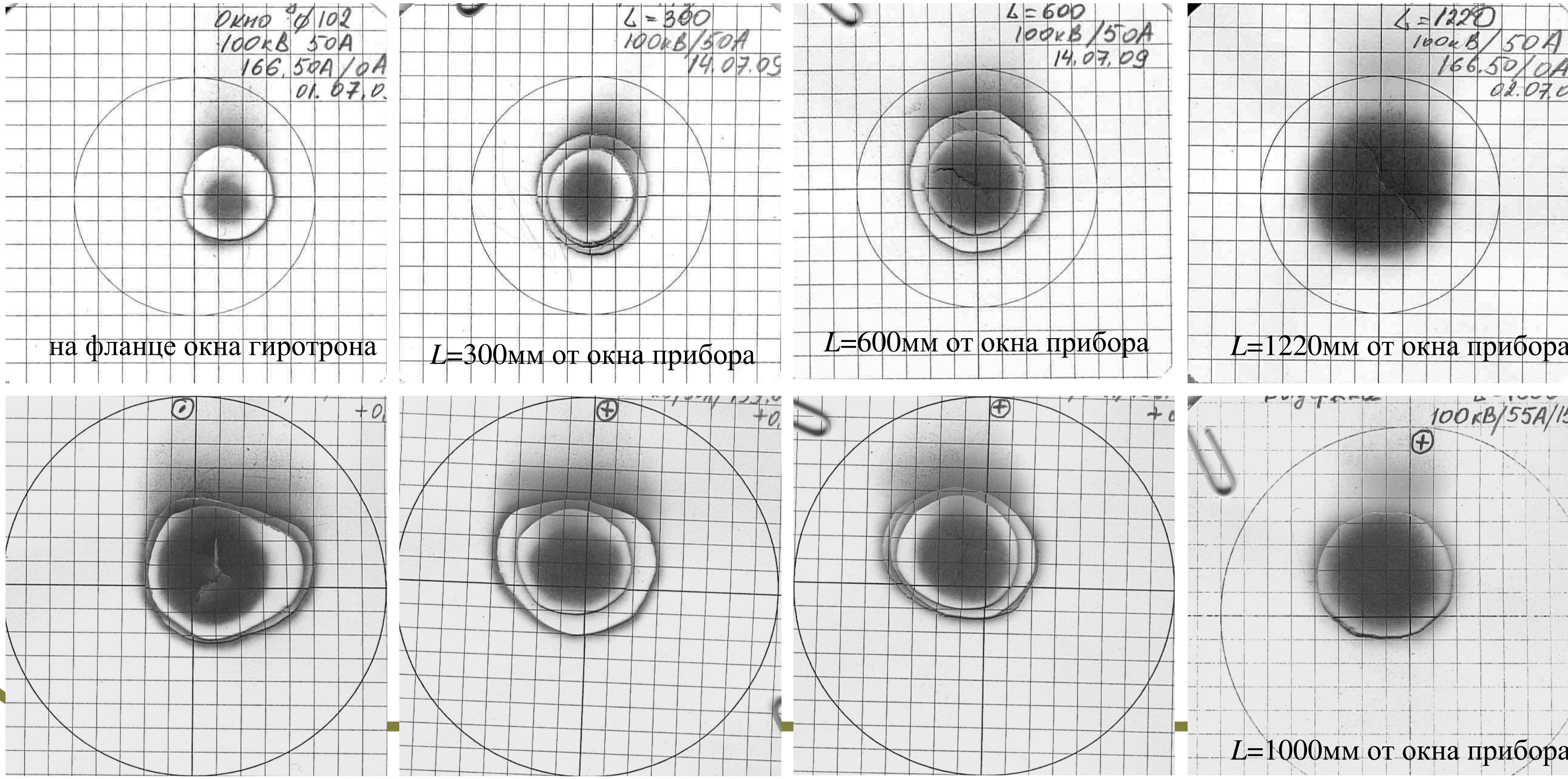
L window-calorimeter	Diff. losses IAP Model-2009
***L*=0 мм**	*P*=1583 kW (100%)
***L*=300 мм**	**- 0.7%** (99.3%)
***L*=600 мм**	**- 1.1%** (98.9%)

28.12 gyrotron

L window-calorimeter	Diff. losses GYCOM_170M2-2010
***L*=0 мм**	*P*=1422 KW (100%)
***L*=300 мм**	**- 1.4%** (98.6%)
***L*=600 мм**	**- 1.7%** (98.3%)



Summary I

- **In short-pulse test of 170GHz/1MW gyrotron maximal output power of 1.2MW and total efficiency of 52% at 1MW level were attained according to ITER requirements. Maximal pulse duration of 800 s at 0.65 MW power and of 200s at 1.05MW were limited by heating of DC insulator.**

- **Two next 170GHz/1MW gyrotrons with upgraded body insulation, modified cooling system for DC-break ceramic, improved design of both output and relief windows has been manufactured and under testing now at the new test facility in Kurchatov Institute having evacuated transmission line**

- **Optimization of magnetron–injection gun and 100μs-pulse testing of 170GHz/1.5MW/gyrotron have been carried out. Generated power up to 2MW and interaction efficiency of about 34% were demonstrated**

Some of MW power level gyrotrons developed and tested in 2005-2009

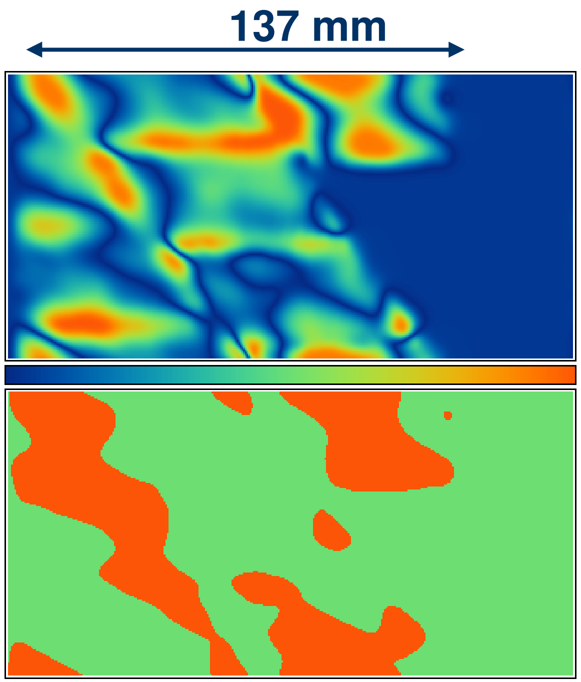
Frequency, GHz	Power	Pulse, sec	Note
Two- and multi-frequency gyrotrons			
105 / 140	0.7 - 0.9 MW	10	2 tubes delivered to ASDEX-Upgrade
147 / 170	0.8/1.0 MW	0.1	CW design, 50% eff
100-150	1.2-1.5 MW	10^{-4}	Short –pulse mock-up, 6 frequencies, high-eff. converter
100-150	0.7-0.8	0.1	Short-pulse mock-up, 11 frequencies, BN Brewster window
105 -140	0.7 – 0.9 MW	0.1 (10)	CW design, 4 frequencies High-eff. mode converter
71.5 / 74.8 / 78.1	0.8 MW	0.1	3 frequencies, 56% eff. BN Brewster window

2009/2010 – repair two ASDEX-Upgrade tubes (frozen; vacuum leak)

Multi-frequency gyrotron. Main problems.

- Effective gyrotron operation at different modes
- Effective conversion of all modes into Gaussian beam
- Tuneable or broadband window

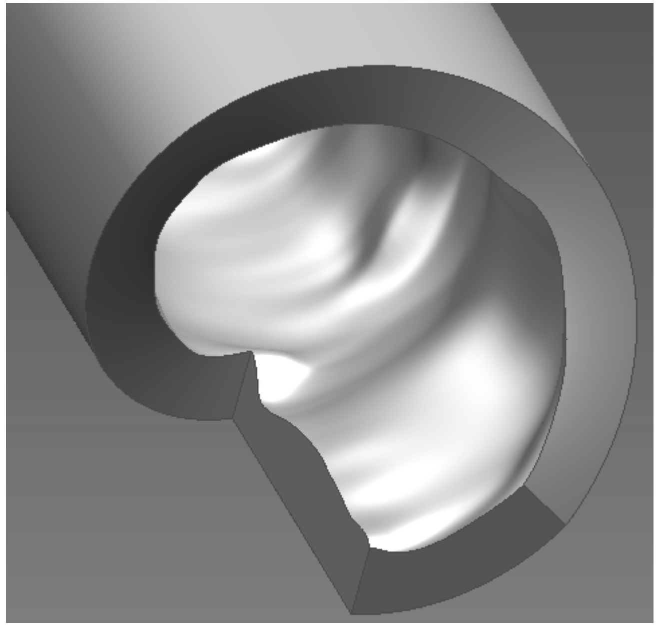
Mode converter for multi-frequency gyrotron 1MW/105…140 GHz



Waveguide deformation
***ΔR(φ,z)*: ±0,31 mm**

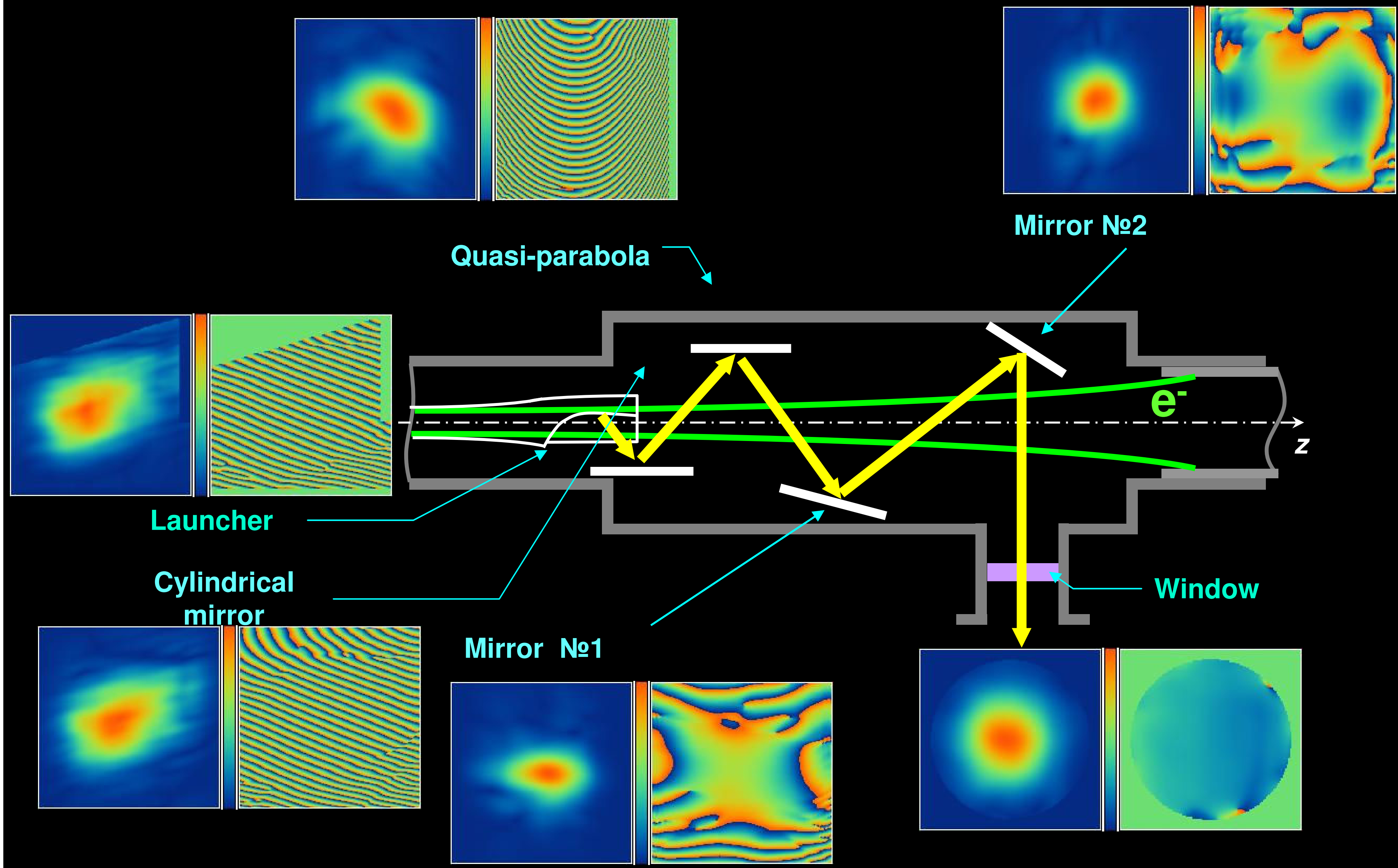
The new converter was successfully tested at 6 modes (!) in a short pulse gyrotron.

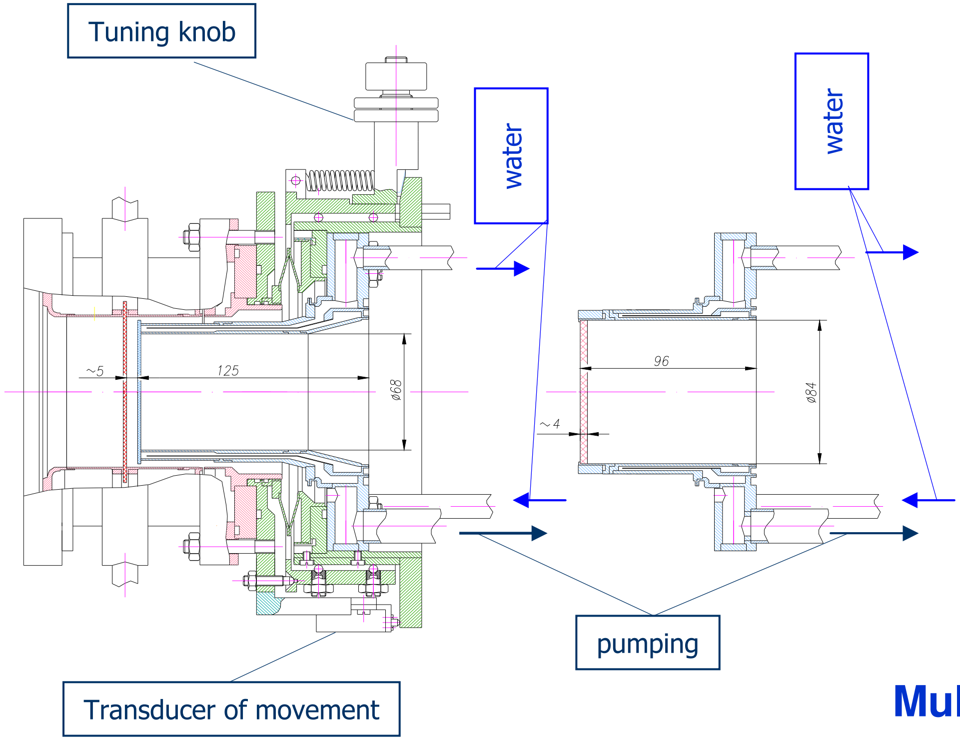
Diffraction losses are less than 2-4% for all modes.



Mode converter launcher
Picture shows10 times exaggerated deformation of the waveguide wall

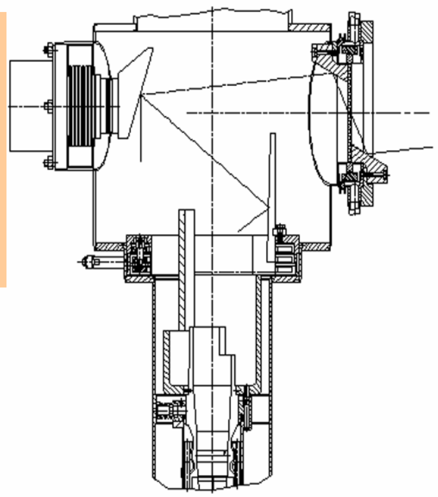
Field patterns in the gyrotron converter (f=140GHz)

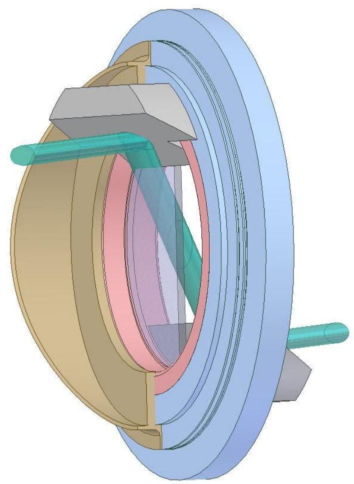




Double disk window

Multi-frequency gyrotron with BN Brewster window

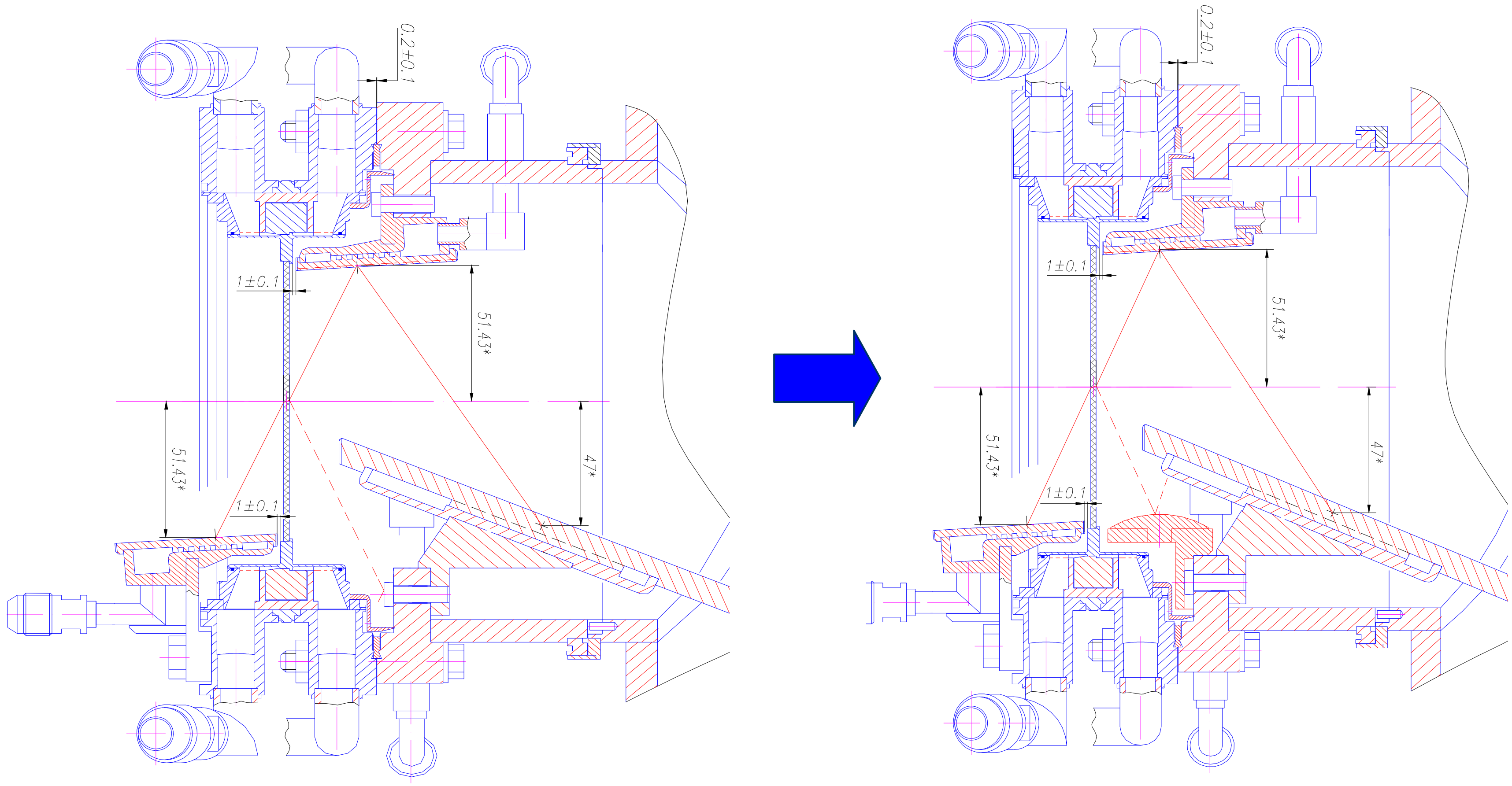




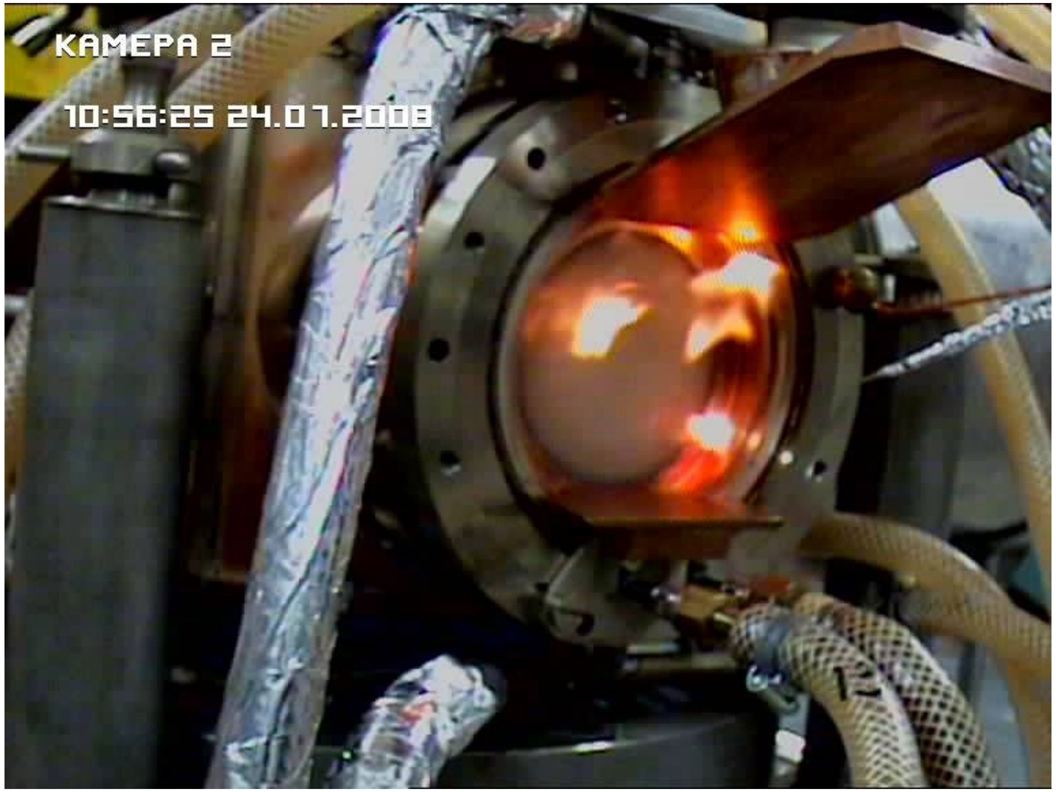
CVD diamond window concepts
in consideration:
- Double-disc tunable window (2005-2009)
- Brewster-angle window (2005-2008)

2009 – corrugated matched disc

Propagation of gyrotron radiation through Brewster-kind output window. Protection of mirror supporting structure against reflected cross-polarized radiation



Multi-frequency gyrotron with Brewster output window: The arc which destroyed the diamond disk



Conditioning regime after a frequency change

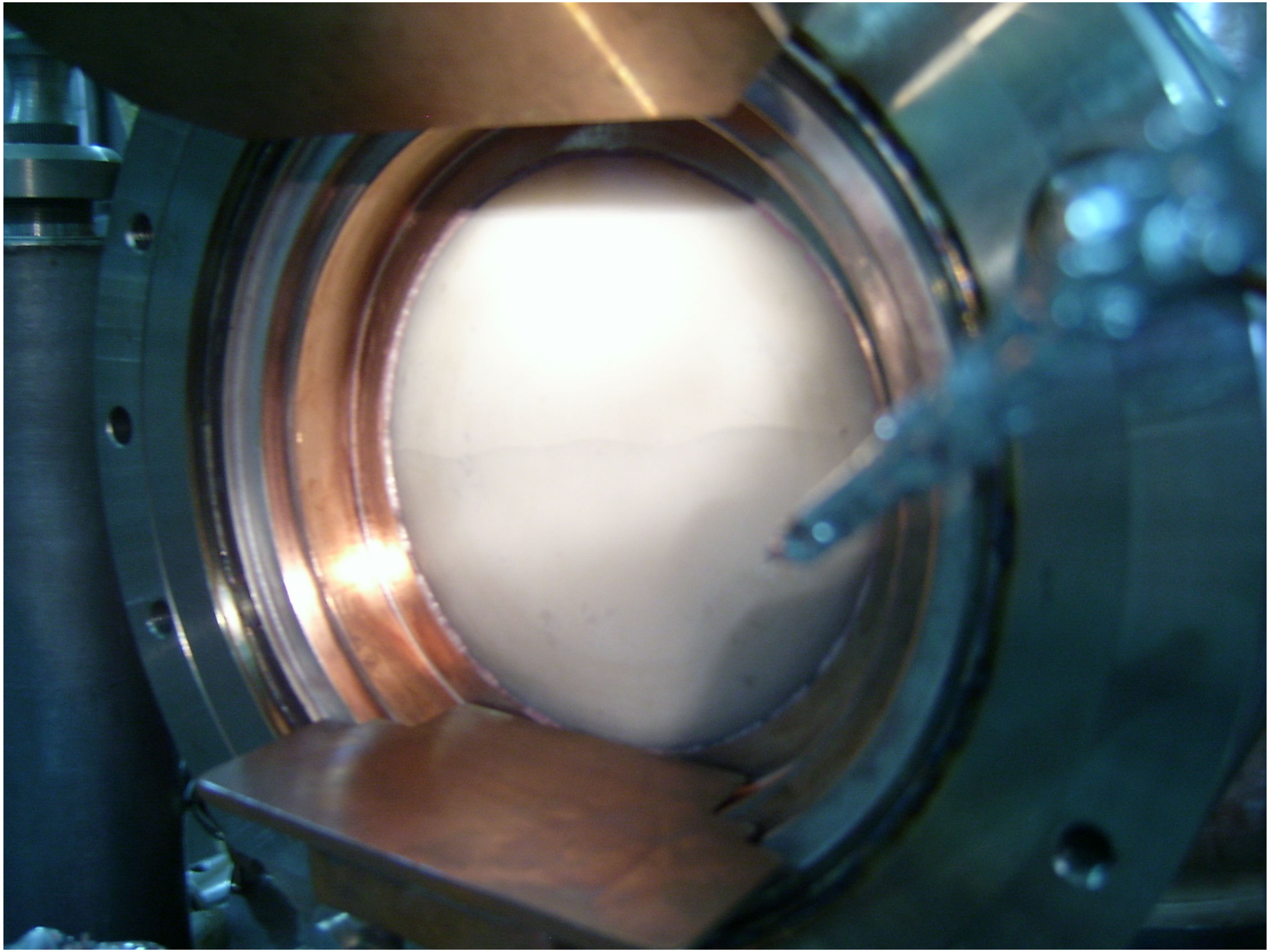
Frequency, GHz	**127**
Output power, kW	**~ 500**
Pulse duration, ms set / actual	**13 / 11**

Diagnostics showed that during the pulse a disruption of the operating regime to generation of the opposite rotating mode happened

It was one of shocks due to arcing which finally destroyed the window disc with internal strengths.

Safety factor (2 in internal strength) was probably too small for a long time operation

Multi-frequency gyrotron window after the failure



SUMMARY II

Last years a significant progress was demonstrated in development of multi-frequency gyrotrons for fusion:

- Two key problems in development of multi-frequency gyrotrons have been solved:
  - Efficient operation of the gyrotron at several modes/frequencies
  - Efficient quasi-optical conversion of all operating modes into Gaussian wave beam
- Several two- and multi-frequency gyrotrons have been developed and tested at MW power level in the ranges of 70-80 GHz, 100-150 GHz, 140-170 GHz with pulses 0.1 -10 seconds
- Gyrotron efficiency of 50%- 60 % has been shown for industrial tubes
- **Design and reliability of multi-frequency gyrotron diamond window is still an issue**