Gyrotrons for Fusion. Status and Prospects

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1. Introduction

Gyrotrons are the most advanced high-power sources of millimeter wavelength radiation. They have been used for many years in electron-cyclotron-wave (ECW) systems of many existing fusion installations. Typically modern gyrotrons produce power of 0.5...0.8 MW in pulses of 2-3 seconds, or lower power in longer pulses (e.g. 300-400 kW in pulses up to 10-15 seconds). For the next generation of fusion installations, such as ITER or W7-X the ECW systems based on gyrotrons capable to produce 1MW/CW radiation are considered. Definitely, such gyrotrons with enhanced performance are very interesting also for the use also at existing installations.

Main problems of elaborating high-frequency CW gyrotrons are associated with attainment of the megawatt RF power level. A modern millimeter wave gyrotron consists of an electron gun, which forms an electron beam with helical trajectories of particles (typical gun voltage is 70...90 kV, current 30...40 A, pitch factor 1.2...1.4), electron beam tunnel, an oversized cavity operating at a high-order mode, quasi-optical mode converter, output window and collector. At the megawatt power level many of gyrotron subassemblies (cavity, window, collector) have to operate at thermal loads close to their limits. There are principal problems to provide high efficiency of the device and absence of parasitic instabilities in the tube in high power regimes of gyrotron operation. The problem of matching the gyrotron output beam of the megawatt power level and the following transmission line proved to be a quite serious problem. And the most acute problem in the recent years was gyrotron window development.

Analyzing the gyrotron development during the last three-four years one may notice that several principal steps were made in development of the megawatt power gyrotrons:

- efficient and stable gyrotron operation was demonstrated at very high order volume modes (for example, $TE_{25.10}$). Operation at such modes allows one to solve the problem of thermal cavity loading;
- demonstration of the depressed collector in high power gyrotrons. This point gives a great move in solving gyrotron collector and power supply problems;
- gyrotron windows made of artificial diamond discs were developed. They are still very expensive but, no doubts, they will help to solve the very old and painful problem of barrier windows.
- successful use of gyrotrons in plasma experiments.

2. High-Order Operating Modes in Gyrotrons

Gyrotrons are capable to produce a very high average power because they operate at very high volume modes of cavities formed by sections of slightly irregular waveguides. Practically every year gyrotron developers show higher and higher gyrotron operating modes. Ten years ago $TE_{15.4}$ (fifteen azimuth and four radial variations) seemed to be a very high gyrotron mode. Several years ago $TE_{22.6}$, mode was a favorite mode for gyrotron developers. In the last years extremely high-order modes $TE_{25.10}$, $TE_{31.8}$ were successfully used in gyrotrons [1,2]. Cavity for the latter modes is approximately twenty wavelengths in diameter.

The main reason to use large size cavities is the problem of thermal loading on the cavity wall. The specific power is limited for gyrotron cavity configuration and technology as $\Delta P/\Delta S$

$< (\Delta P/\Delta S)_{crit} = 2\text{-}3$ kW/cm^2 and power enhancement is strictly linked with cavity size increase. Typical diffraction Q-factor for fusion gyrotrons is 1000-1500, Ohmic quality depending on the cavity size and wavelength is of the order of 50000, so several per cent of power (tens kilowatt) is dissipated in the cavity. This power and its density require very advanced cooling systems for gyrotron cavities.

The use of very high-order modes in gyrotrons brings some principal problems. The main problem is stable and efficient gyrotron operation. Recent calculations and experiments give a feeling that operating modes with indexes 60-70 are near the limit for gyrotron operation with acceptable efficiency (not less than 30% without collector energy recovery) in sufficient (not extremely small) area of the magnetic field and voltage [3]. A further increase of cavity size requires additional ways of mode discrimination. One of the tested ways is the use of a coaxial insert into the cavity. Such an insert of a proper diameter and shape makes diffraction quality of some parasitic modes lower. Rather sophisticated methods [4,5] based on optimization of the insert profile and surface impedance resulted already in successful gyrotron operation at modes with extremely high transverse indexes as $TE_{28.16}$ and $TE_{31.17}$, (cavity diameter $\varnothing_C \approx 30\lambda$).

3. Sub-assemblies of Modern Gyrotron

Gyrotrons for fusion systems are developed by several companies and institutions. The scheme of the most advanced gyrotrons are similar for all companies. There are also similar definitions of gyrotron sub-assemblies. We shall enumerate them and indicate critical points and principles of component development.

Electron gun and beam tunnel is intended to form an intense electron beam with design parameters. The goals of optimization are maximal transverse energy $(V_\perp/V)^2$, small velocity spread $(\Delta V_\perp/V_\perp)$ and prevention of instabilities in a beam tunnel. This component is usually optimized thoroughly on the base of special codes.

Cavity sizes and its quality factor depend on electron beam parameters. A very critical parameter is the thermal loading of the cavity. There are some contradictions in providing simultaneously high gyrotron efficiency and relatively low specific Ohmic losses. The compromise is achieved in numerical optimization of cavity/electron beam parameters and very often the parameter choice is checked in a so-called short-pulse gyrotron prototype.

Quasi-optical mode converter transforms a high-order operating mode into a paraxial wave beam with linear polarization and separates electron and wave beams. The electron beam goes to the collector and the wave beam usually comes out of the tube in the direction perpendicular to the magnet axis. This separation gives the possibility to solve collector and window problems practically independently. The mode converter consists of a special irregular cut ending waveguide up-taper from the cavity, quasi-parabolic reflector and one or two specially shaped mirrors. Sometimes more mirrors are applied to transmit the wave beam inside the magnet. The converter forms an optimal spatial field structure over the window surface: the flattened distribution for long pulse gyrotrons with ceramics (BN) windows, where thermal conductivity of window material is relatively low, or Gaussian distribution (optimal for wave beam transmission) for diamond windows.

The mode converter is an open mirror line and there are diffraction losses inside a gyrotron. For the megawatt tube the acceptable level of these losses is 3...5 %. There are methods to provide so low diffraction losses: pre-shaping of the wavebeam before its launching from the guide cut, and synthesis of the quasi-optical reflectors [6]. By the first method the field of the operating wave is shaped (by means of small irregularities of up-taper) even before its radiation from the cut. The shaped beam has weak fields at the cut edges (lower diffraction) and a nearly Gaussian angle spectrum. The second method allows one to synthesize a desired field structure of paraxial wavebeams.

In fact, the mode converter ends outside the tube. The output wave beam before its use practically in all cases passes through so-called ***matching optics*** which adjust the beam to the following transmission line. To do this accurate wavebeam measurements are needed. High-power beams structure measurements may be performed by means of infrared camera recorded thermal traces of the beam passing through thin dielectric films. Having measured intensity distributions one can perform phase front retrieval [7] and after that mirror synthesis for the beam conditioning.

Electrons after separation from the wave beam come to a ***collector***, which is the biggest part of a megawatt gyrotron. A tremendous power (2-3MW) is to be dissipated on the collector surface. This results in huge water consumption of 20-30 l/sec. The collector has large diameter 200-300 mm and length of about 1 meter. For some gyrotrons electron beam sweeping is applied to distribute it over collector surface. A principal step in gyrotron development was demonstration of possibility of electron energy recovery in collectors with potential depression. This point is discussed below.

Microwaves leave the tube through a ***barrier window***. For pulse gyrotron operation up to several second pulse duration the windows are made of ceramics as BN or SiN. The ceramics windows are convenient in use, however, because of low thermal conductivity pulse duration is limited (1MW/110GHz/2sec) and average transmitted power does not exceed 100-200 kW. Ceramics windows at extreme parameters of operation withstand temperatures higher than 1000 C. Even in such conditions they operate quite reliably.

There were many concepts to develop CW window capable to transmit megawatt power microwaves. Now all these concepts lost in competition with windows on the base of artificial (produced by CVD technology) diamonds.

4. Depressed Collectors in High Power Gyrotrons

The possibility of energy recovery of electrons in gyrotrons was discussed for the first time many years ago [8]. The problem was not very acute for gyrotrons with moderate average power (kilowatts) and, of course, short pulse tubes, where efficiency enhancement of the tube with a depressed collector is compensated by more complicated tube design with an additional insulator and an additional power supply unit. The problem showed up itself when the development of megawatt power, CW gyrotrons for ITER began. Extraordinary power dissipated at the collector (and corresponding water flows) and strict requirement to over-total efficiency of the tube bring back depressed collectors to consideration.

Along with efficiency enhancement (for real tubes efficiency increase is about 1.5 times) there are obvious but very impressive drop in the power dissipated on the collector. So the efficiency increase from 33% to 50% makes the dissipated power two times lower: 1 MW instead 2 MW for the megawatt power output. It is reasonable to stress that the main (high current) power supply operate at lower voltage and, also, the electron beam with lower energy causes significantly lower intensity of X-rays.

The return to depressed collectors for megawatt power gyrotrons in the experiment was very impressive [9]. Later on other groups demonstrated essential efficiency enhancement [10,11]. Nowadays gyrotron efficiency of 50% seems to be more a routine than a record.

The series of CPD gyrotrons was produced and tested by GYCOM in the period 1996-2000. Below the experimental results for long pulse (1…3 s) gyrotrons are presented.

TABLE I. GYROTRONS REGIMES WITH MAXIMUM OUTPUT POWER

	70 GHz	82.7 GHz	84 GHz	140 GHz	170 GHz
Total voltage U_{beam}	78.5 kV	75.5 kV	85 kV	90 kV	73 kV
Cathode voltage U_{cath}	-49.5 kV	-50 kV	-55 kV	-60 kV	-57 kV
Beam current I_{beam}	28.5 A	24.5 A	30 A	36 A	27 A
Output power P_{out}	**680 kW**	**650 kW**	**930 kW**	**1040 kW**	**700 kW**
Efficiency η	48%	53 %	56 %	48 %	46%
Pulse duration τ	3 s	3 s	2 s	1 s	1 s

TABLE II. GYROTRON REGIMES WITH MAXIMUM EFFICIENCY

	70 GHz	82.7 GHz	84 GHz	140 GHz	170 GHz
Total voltage U_{beam}	78.5 kV	75.5 kV	85 kV	90 kV	73 kV
Cathode voltage U_{cath}	-49.5 kV	-50 kV	-55 kV	-60 kV	-55 kV
Beam current I_{beam}	22 A	21.5 A	27 A	31 A	25 A
Output power P_{out}	583 kW	591 kW	840 kW	940 kW	650 kW
Efficiency η	**53.5 %**	**55 %**	**56.5 %**	**50.5 %**	**48 %**
Pulse duration τ	3 s	3 s	2 s	1 s	1 s

5. CVD Diamond Windows for Gyrotrons

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 and very high (about four times higher than for copper) for a very wide temperature range
- low losses of microwaves. Loss tangent less than 10^{-5} at millimeter waves was demonstrated for several discs
- extremely high mechanical properties. For example, the disc of 1.5 mm thickness and 100 mm diameter can withstand several bars of gas pressure.

The properties of artificial diamond discs were improved essentially during last years. The discs with diameter about 100 mm, thickness 1.5-2 mm, loss tangent $1\text{-}3\cdot10^{-5}$ at short millimeter waves, thermal conductivity 20W/cmK are available now. They are still very expensive, but in fact the window based on an artificial diamond nowadays is the only window version which solves the problem of a megawatt CW window [12,13]. Calculations show that the windows based on the best discs are capable to transmit even 2-3 MW power.

Diamond discs allow one to use the window with edge cooling by water at room temperature. This fact is a principal point which makes use of gyrotrons much more comfortable as compared with previous window schemes operating at cryogenic temperatures or using some sophisticated (and sometimes even dangerous) coolants. A very extensive study of electrical, mechanical and heat properties of CVD discs is carried out at FZK [12].

There are several manufacturers of diamond discs: the famous De Beers holds the major positions, other groups and companies, which are trying to produce cheaper discs, do not yet play essential role on the market. One more company (besides De Beers) from Russia "Digascron" produces CVD discs of very high quality [13]. Russian discs have up to now limited diameter (less than 65 mm) and thickness (less than 1.5 mm).

Diamond discs for gyrotron windows have to be brazed to metal constructions with a high temperature alloy in order the tube can pass the process of baking out. This is a difficult problem because diamond and metal parts have very different thermal expansion. There is a way to braze the diamond discs on the base of Aluminum. This kind of brazing limits the maximal temperature of baking out as 400-450 C, however the main part of the brazed discs made in such a way. High temperature brazing is now also under development in several groups. There are positive results of brazing diamond discs of 60mm diameter to copper cuffs with melting temperature of the alloy 750 C.

Several tubes with diamond windows have been fabricated and tested by different institutions and companies [14,15]. Test results are very encouraging in spite of natural problems when a new key component is implemented in a tube. Some gyrotrons with diamond windows are already used at plasma installations (DIII-D, JT-60)

6. Use of gyrotrons at fusion experiment

Ten years ago there were very few fusion installations where gyrotron complexes were used for plasma parameters control. There were no installations, which exploited megawatt power level gyrotrons. Since that time the situation has changed dramatically. Now practically each fusion installation has a gyrotron complex. Last experimental campaigns on many toroidal devices and especially results on MHD stabilization and ECCD at discharges with internal barrier at Asdex-UG and sophisticated experimental ECH schemes at stellarator W-7AS have demonstrated conversion of ECH and ECCD systems based on gyrotrons into a routine instrument for fusion experiments. The progress became possible due to industrial production of reliable gyrotrons in the entire millimeter wave band with the power ≥ 500 kW and a few second pulse duration.

7. Perspectives

Megawatt power CW gyrotron at millimeter wavelengths is feasible. Definitely it will be demonstrated in a few years. For the next round of gyrotron development there are two more demands and two directions: development of multi-megawatt microwave power source and frequency tunable megawatt gyrotrons. The work on these extremely ambitious and difficult problems is carrying out. Projects of multi-megawatt coaxial gyrotrons and step-frequency-tunable gyrotrons are now at the stage of studying pulse prototypes. Gycom is planning to test industrial version of long pulse 2 MW 140 GHz coaxial gyrotron with depressed collector at the mid of 2001. A CPD one megawatt/long pulse gyrotron operating at two frequencies is also under development at Gycom. The short pulse (50 msec) prototype generating 1.05 MW at 140 GHz and 0.9 MW at 104 GHz with efficiency over 50% was already demonstrated.

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