GYROTRONS FOR ECR ION SOURCES

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Résumé

L'amélioration des performances des sources d'ions excités à la résonance cyclotronique (ECR) requiert des générateurs microondes délivrant en continu une dizaine de kilowatts à des fréquences supérieures à 20 GHz. Les générateurs conventionnels, comme les klystrons où les tubes à ondes progressives atteignent la limite de leur capacités dans ce domaine, il est naturel de considérer comme alternative les gyrotrons. Après un rappel de la physique de gyrotron, nous présentons les deux concepts présentement développés par ABB, c. à d.: le gyrotron à cavité cylindrique et le gyrotron quasi-optique.

Les divers aspects technologiques ainsi que l'opération de tels oscillateurs seront discutés en utilisant, comme illustration, un tube de 400 kW à 8 GHz en cours de test.

Nous décrivons des études conceptuelles de gyrotrons à cavités cylindriques et de gyrotrons quasi-optiques spécialement conçus pour les sources d'ions ECR. Leur performances sont: fréquence 30 GHz; puissance 20 kW. Le champ magnétique correspond à une opération à la fondamentale ou à la seconde harmonique de la fréquence cyclotronique. Les problèmes au transport du faisceau microonde du générateur à la source d'ions seront également discutés.

Abstract

To increase the performance of future ECR ion sources, microwave sources at frequencies above 20 GHz at cw power levels of some 10 kW are required. As conventional microwave tubes, like Klystrons or TWTs reach their limit at about these values, the application of gyrotron tubes is considered.

The paper describes first the physics of the gyrotron interaction. Then the two gyrotron concepts pursued by ABB are presented, the cylindrical and the quasi-optical gyrotron, respectively. The technical realisation and the operation of a gyrotron oscillator is demonstrated with some experimental results of an 8 GHz, 400 kW tube presently under test.

The layout of low power gyrotron oscillators for ECR plasma heating at 30 GHz with a cw output power of 20 kW follows. Operation at 1st and 2nd harmonic for both gyrotron concepts is evaluated. Finally some ideas concerning the r.f. transmission line and wave launching structure into an ECRIS are shown.

1. Introduction

Since the beginning of Electron Cyclotron Resonance Ion Source (ECRIS) development, more than a decade ago, considerable progress has been reported for both ion charge state and intensity of the highly charged particles /1/2/. Most of the progress was achieved by improving the plasma confinement structure and increasing the ECR heating frequency. Today this type of ion source has attained a firm place in many atomic physics laboratories and on ion accelerators, whose efficiency could be greatly enhanced by the use of highly charged particles /3/.

Practically all existing ECR ion sources are heated by magnetrons or klystrons in the frequency range between 2.45 GHz and 16 GHz at a power level of several kW. Indeed, it is known for long, that charge states and beam intensity of an ECRIS grows with frequency and power of the microwave launched into the magnetically confined plasma /4/. However, the output power capability of conventional microwave tubes falls off drastically at frequencies above 10 GHz, in particular for long pulse or continuous wave (cw) operation, because of the power loading problems of their minute microwave circuits (see Fig.1).

Fig.1 Cw power handling limit of conventional microwave tubes and nowadays gyrotrons

For the next generation of ECR ion sources power levels above 10 kW in the frequency range around 30 GHz are required. These specifications can easily be fulfilled by GYROTRONS. Although gyrotron tubes have primarily been developed for fusion plasma heating in the power range of hundreds of kW at frequencies between 8 and 300 GHz, these tubes can be scaled down to moderate cw power levels at reasonable cost and dimensions suited for ECRIS heating. In this paper the physics of the gyrotron operation is reviewed followed by the description of the two gyrotron concepts, the cylindrical and the quasi-optical gyrotron, respectively. The performance characteristics of a gyrotron will then be demonstrated with an ABB 8 GHz tube, presently under development. Finally the layout and specifications of gyrotron oscillators designed for ECRIS heating and some examples for microwave transmission lines are presented.

2. The Physics of the Gyrotron

The generation of microwaves in a gyrotron is based on the exchange of energy between a slightly relativistic electron beam and the electromagnetic fields inside an open resonator (cavity), at the electron cyclotron resonance (ECR) condition (cf. Eq.3).

In contrast to traditional microwave tubes, the operating frequency ω of the gyrotron is essentially determined by the externally applied dc magnetic field B_0 , which forces the beam electrons to gyrate with the cyclotron frequency ω_c along the lines of magnetic flux through the resonator. Figure 2 shows a schematic of a gyrotron oscillator together with the static magnetic field B_0 and the r.f. field $|E|$ along the axis of the cavity.

Fig.2 Schematic of a gyrotron oscillator with static magnetic field B_0 and cavity r.f. field $|E|$

The relativistic cyclotron frequency ω_c is related to B_0 by

$$\omega_c = \frac{e}{m_e} \cdot B_0 \quad (1)$$

where e is the electron charge and m_e the relativistic electron mass:

$$m_e = m_0 \cdot \gamma = \frac{m_0}{\sqrt{1 - \left(\frac{v_e}{c}\right)^2}} \quad (2)$$

in which m_0 is the electron rest mass, γ the relativistic factor, v_e the electron velocity, and c the velocity of light in vacuum.

The operating frequency ω_{rf} of the gyrotron and ω_c are related through the ECR condition

$$\omega_{rf} = n \cdot \omega_c \quad (3)$$

Effective interaction occurs only for magnetic fields where n is near integer values. For most microwave field shapes the fundamental resonance condition with $n \approx 1$ has the strongest interaction. With special field shapes, useful interaction can take place with larger values of n . These harmonic interactions have the advantage that the magnitude of the dc magnetic field for a given frequency can be reduced by $1/n$, however, at the cost of lower electronic efficiency. For the fundamental resonance condition, a frequency of 28 GHz requires a 1 Tesla magnetic field. For higher frequencies, proportionally higher fields are needed, leading to the use of superconducting magnets for fundamental operation above 30 GHz.

Fig.3 Section through a TE_{01} gyrotron resonator with annular electron beam radial field distribution E_φ

Due to the correlation of the operating frequency of the gyrotron to the gyrating frequency of the electrons in the applied magnetostatic field, the beam and microwave circuit dimensions can be several times the wavelength, thus avoiding the power density problems encountered in klystrons or travelling-wave tubes for the same frequency. As a result, the continuous microwave output power can be increased by orders of magnitude. Figure 3 shows a cross-section through a gyrotron resonator operating in the TE_{01} mode with the annular electron beam and the azimuthal electrical resonator field as they would appear at the entrance of the interaction cavity. The position of the individual electrons is arbitrary and not yet optimal for energy extraction. The optimum position is achieved by speeding up or retarding the electrons (phase bunching) in the electromagnetic field of the resonator. This bunching of the electron beam occurs as a result of a relativistic effect. It can be seen from equation (1), where an increase in electron kinetic energy results in a decrease of the angular velocity or gyrating frequency of the electron and vice versa. In a gyrotron oscillator the microwave electric fields in the early part of the cavity apply an angular velocity modulation to the electrons. As the beam drifts further through the cavity, angular bunching of the electrons takes place as a result of the angular velocity modulation. This effect is shown schematically in Fig. 4. Towards the end of the cavity the phase between the electron bunches and the microwave electric fields is adjusted so that a net

transfer of kinetic energy from the electrons to the microwave occurs. When the energy given up by the electrons exceeds the cavity losses, an oscillation results and output power is available from the gyrotron.

Fig.4 a) Particle distribution in the momentum plane (P_x , P_y) at the beginning of the interaction. The electrons are uniformly distributed on a circle of radius $P_{\perp 0} = (P_x^2 + P_y^2)^{\frac{1}{2}}$.
 b) Due to the interaction with the electromagnetic wave, the relativistic factor γ of different electrons changes. They are no longer uniformly distributed on the circle but are "bunched" in the positive P_x half-plane where a net transfer of energy from the electron-beam to the wave occurs [5].

Due to the relativistic effect involved in the interaction process, gyrotrons require beam voltages from 50 to 100 kV for efficient operation.

3. The Conventional and Quasi-optical Gyrotron

At ABB work is currently being carried out on two gyrotron concepts. In the conventional or cylindrical gyrotron (Fig. 5a) a so-called magnetron injection gun (MIG) creates an electron beam with a toroidal cross-section. The electrons are emitted radially from an annular cathode and given both a radial and an axial component of velocity which, in presence of the axial magnetostatic field provides the cyclonic motion of the electrons. After magnetic compression by the increasing static B-field, the beam enters the resonator carrying the major part of its energy in the gyration movement of the electrons:

$$\alpha = \frac{V_{\perp}}{V_{\parallel}} \geq 1.5 \quad (4)$$

with $V_{\perp}$: perpendicular velocity
 $V_{\parallel}$: axial velocity

After passage through the interaction cavity the electron beam continues towards the collector, where it is dissipated on an water-cooled wall. The r.f. wave exits through a vacuum window which is transparent to microwaves.

Fig.5 Principle of a conventional and quasi-optical gyrotron

The quasi-optical gyrotron's beam (Fig. 5b) is generated in the same way as the cylindrical gyrotron's. However, here the resonator is a Fabry-Pérot one with two spherical mirrors arranged perpendicular to the beam. At least one mirror is partially transparent for coupling out the microwave beam.

Although it is technically more complex, the quasi-optical gyrotron incorporates some important benefits [6]:

- By choosing an appropriate mirror geometry the resonator can be optimized for maximum interaction efficiency keeping the thermal loading of the resonator mirrors always within tolerable limits (1.5 kW/cm²).
- The gyrotron frequency can be tuned continuously within 10% by varying the magnetostatic field at the resonator and the distance between the mirrors.
- Since the r.f. beam and the electron beam are decoupled, an electrically depressed collector can be used to partially recover the unused electron beam energy; i.e. increasing the overall tube efficiency.
- The linearly polarized output mode can be transported without major mode conversion by a low loss quasi-optical transmission line.

4. Gyrotron Performance Characteristic

The technical layout and the general performance characteristic of a gyrotron oscillator will be demonstrated with two ABB tubes being presently under development, an 8 GHz cylin-

drical tube designed for 500 kW cw output power and a 115 GHz quasi-optical tube for 150 kW in pulsed operation /7/.

Figure 6 shows the layout of the GT 8-500c tube with its magnet system and high voltage insulation tank. Unlike other commercial gyrotrons which are usually operated with an oil insulated triode electron gun this tube is equipped with an SF_6 insulated diode gun. This requires a less complex high voltage power supply without major drawbacks for cw operation. The cathode is operated at -80 kV; switching and regulation is provided by a high voltage tetrode (ABB CQK 200-4). Gun, resonator, collector and r.f. window are water-cooled. The tube is permanently pumped by 2 ion getter pumps allowing at the same time to monitor the vacuum, which should always be better 10^{-7} mbar. Potential breaks on both ends of the collector allow to monitor independently the fraction of the electron beam being intercepted by the body, the collector and the output window of the tube.

Fig.6 Layout of the ABB 8 GHz gyrotron oscillator for 500 kW cw (GT8-500c)

The main solenoids for the resonator magnetic field of 0.32 Tesla are water-cooled; the gun solenoids to adjust the compression of the beam to the resonator are uncooled, as well as the collector solenoids to control the spreading of the spent beam to minimize the specific loading of the collector. Figure 7 shows a schematic of a gyrotron power supply with its connections to the tube, here including a modulation anode.

Fig.7 Schematic of a gyrotron power supply

The cathode of a gyrotron is generally operated in temperature limited regime allowing to control the beam current and r.f. output power by the temperature of the indirectly heated dispenser cathode. Figure 8 shows the measured output power and efficiency of the 8 GHz prototype GT 8-2c as function of the beam current. It should be noted, that the output power can be smoothly adjusted from 0 up to more than 300 kW by varying the heater current of the cathode between 7 and 10A (11V). Up to 42% efficiency was measured. The gyrotron has operated successful with up to 50% reflected power from mismatched load /8/. The output mode of this tube was determined with a k-spectrometer /9/ to be almost 100% TE_{01} . Figure 9 shows a picture of the 8 GHz gyrotron being 2.2 m long.

Fig.8 Measured output power and efficiency as a function of beam current for the 8 GHz gyrotron prototype GT8-2c

Fig.9 Picture of the 8 GHz prototype tube GT8-2c

For the other type of gyrotron, the quasi-optical, a 100 GHz teststand is in operation since end of 1987, showing the anticipated linearly polarized output mode. Tunability of the frequency was demonstrated by changing the distance of the resonator mirrors ⁽¹⁾.

Another compact quasi-optical gyrotron for 115 GHz presently under assembly, is shown in Figure 10. Here the cryostat for the superconducting resonator magnets serves as vacuum container for the tube. The gyrotron is designed for 150 kW output in ms pulses, but can later be upgraded to cw and higher power using depressed collector technology. As the quality factor of the Fabry-Pérot resonator is generally high ($Q > 30\,000$) no significant load sensitivity is expected.

(1) Private communication of the CRPP/ABB Quasi-Optical Gyrotron development group.

Fig.10 Layout of a compact quasi-optical gyrotron for 115 GHz and 150 kW pulsed power

5. Gyrotron Concepts for ECRIS

A preliminary study was performed to evaluate the working data for low power gyrotrons applicable to ECR ion sources. The following target specifications were selected:

Frequency	:	30 GHz
Output power:		20 kW
Operation	:	cw
Design	:	compact

Operation at first and second harmonic was considered for both concepts, the cylindrical and the quasi-optical gyrotron.

As an output power of only 20 kW has to be achieved, the beam voltage was fixed to 50 kV ($\gamma = 1.1$), lowering the requirements for the electron gun power supply, however, at some cost of tube efficiency.

5.1 Cylindrical Gyrotron Design

For the cylindrical approach a TE₀₂₁ cavity was chosen with the electron beam placed on the first radial maximum of the electric field.

The gyrotron operating at the first harmonic requires a static magnetic field of 1.18 Tesla which can be established by conventional water-cooled solenoids. However, taking the running costs into account a superconducting magnet with persistent mode switch and low helium consumption could be an attractive alternative. Choosing a cavity Q of 1000 an electronic efficiency of 39% was calculated. The corresponding beam current is 1.03 A. The average ohmic loss inside the cavity less than 50 W/cm² which does not cause any cooling problems.

The technical layout of the gyrotron would be rather similar to Figure 6 except for the overall length, being less than 1 m. The diameter of the output waveguide for TE₀₂ mode is about 5 cm.

At the same magnetic field a second harmonic gyrotron could oscillate at 60 GHz with a reduced efficiency of about 30%. In this case the cavity has to be scaled down for the shorter wave length to 1.16 cm diameter and 2.75 cm length.

Another interesting solution for the 30 GHz gyrotron is the operation at second harmonic in a magnetic field corresponding to 15 GHz fundamental operation. The required B-field would then be only 0.59 Tesla which can easily be achieved over the necessary resonator length of 5.5 cm. The efficiency of this tube version is also about 30%, requiring a beam current of 1.33A to achieve an output power of 20 kW.

Table 1 summarizes the parameters for the cylindrical gyrotron design.

Table 1 Preliminary specifications of cylindrical 1st and 2nd harmonic gyrotrons with 30 GHz, 20 kW cw

		1 st harmonic	2 nd harmonic
Beam voltage	U_b	50 kV	
Beam current	I_b	1.1 A	1.33 A
Beam radius	R_e	0.293 cm	
$\alpha = v_{\perp} / v_{\parallel}$		1.5	
Cavity mode		TE ₀₂₁	
Cavity Q	Q	1000	> 5000
Cavity B-field	B_0	1.18 T	0.59 T
Cavity radius	a	1.12 cm	
Cavity length	L	~ 5.5 cm	
Electronic efficiency	η	39 %	30 %

5.2 Quasi-optical Gyrotron Design

For the same beam parameters as before a design for a quasi-optical gyrotron working at 30 GHz was established. The resulting calculated efficiencies are 20% for first harmonic and

16% for second harmonic operation, respectively. Because of the separation of the electron beam and the microwave, the quasi-optical gyrotron can easily accommodate a depressed collector which would increase the tube efficiency by about a factor of 1.6. At the same time the voltage requirements for the beam power supply are decreased to about 30 kV. Figure 11 shows the layout of a tunable quasi-optical gyrotron with conventional magnets. Again, the second harmonic operation at half of the B-field seems to be an attractive solution, although the efficiency is rather low.

Fig.11 Scheme of a tunable quasi-optical gyrotron (30 GHz, 20 kW, cw) for an ECRIS

Table 2 summarizes the results for the quasi-optical gyrotron version.

Table 2 Preliminary specifications of quasi-optical 1st and 2nd harmonic gyrotrons with 30 GHz, 20 kW, cw

		1 st harmonic	2 nd harmonic
Beam voltage	U_b	30 kV	
Beam current	I_b	2 A	2.5 A
$\alpha = v_{\perp} / v_{\parallel}$		1.5	
Cavity mode		TEM ₀₀	
Cavity Q	Q	45300	> 100000
Cavity B-field	B_0	1.18 T	0.59 T
Mirror spacing	d	30.7 cm	
Mirror radius	r_0	9 cm	
Mirror transmission	T	1 %	
Electronic efficiency	η	20 %	16 %

6. Transmission lines

After its generation the microwave power has to be transmitted and launched into the ion source plasma. Corresponding to the output mode of the gyrotron, different transmission lines are proposed.

Fig.12 Layout of a TE_{01} -transmission line from a cylindrical gyrotron to an ECRIS

The cylindrical gyrotron delivers its power in the TE_{02} mode. Figure 12 shows the schematic of a waveguide system from the cylindrical gyrotron to the ECRIS. The first element of a long pulse transmission line is usually an arc detector for the protection of the cooled output window in case of a flashover inside the line. Then the TE_{02} mode has to be converted into the low loss TE_{01} mode. This is accomplished by an element whose cross-section varies with the beatwave length of the two corresponding modes. For changing the waveguide orientation from the vertical gyrotron output to the horizontal ECRIS input at least one TE_{01} -bend is needed. This can be a waveguide element with suitable curvature and adapted length to avoid conversion into an asymmetric mode, or a TE_{01} mitre bend. The straight TE_{01} line section is a simple tubular waveguide. For the injection of the wave into the ion source it might be necessary to convert the TE_{01} mode down to standard rectangular TE_{10} mode, because of space limitations at the microwave entrance port. The conversion can be done efficiently by a so called Marié or a King-converter which has to be cooled for steady state operation. The microwave window of the source would also require some cooling. To protect the gyrotron in case of excessive power reflection from the plasma, directional couplers are recommended to trigger the switching-off of the electron beam voltage. It should be noted, that the gyrotron is not as sensitive to load reflection as a klystron tube, whose output cavity is overloaded soon.

The quasi-optical gyrotron delivers its output power as a gaussian-like microwave beam (TEM_{00} -mode) which is diffracted around one of the resonator mirrors. The microwave output is horizontal.

One way of guiding the power to the ECR source is to convert the TEM_{00} -mode with a corrugated waveguide taper into HE_{11} (see Fig. 13) HE_{11} is a hybrid mode of 85% TE_{11} and 15% TM_{11} . Low loss transportation of the HE_{11} wave can be accomplished by corrugated circular waveguides. If needed, low loss mitre bends should be used. Incident and reflected power can be monitored through small coupling holes. Finally, the wave is injected into the ECRIS through a further downtaper and a cooled microwave window.

a) HE_{11} (85% TE_{11} , 15% TM_{11})

b) TEM_{00} (Gauss profile)

Fig.13 Layout of an HE_{11} (a) and TEM_{00} (b) transmission line from a quasi-optical gyrotron to an ECRIS

Another way of guiding the TEM wave of the quasi-optical gyrotron to the ion source is to use a fully quasi-optical transmission system. A cassegrain antenna directs the TEM beam via a focusing mirror line to the entrance window of the ECRIS. This way the entrance port of the ion source can be minimized up to its breakdown limit. Directional power measurement is provided through small coupling holes inside a mirror. As the quality factor of the quasi-optical gyrotron's resonator is very high ($Q > 40000$), the sensitivity to load reflection is expected to be negligible.

7. Conclusion

For the next generation of ECRIS microwave sources in the frequency range of 30 GHz with a steady state output power of about 20 kW are needed. An attempt was made to scale existing ABB gyrotron designs down to meet these specifications.

Two gyrotron concepts, the conventional and the quasi-optical, were investigated for first and second harmonic operation leading to 4 feasible tube versions having different characteristics:

- The first harmonic cylindrical gyrotron is the most efficient tube ($\eta = 39\%$). The electron gun requires 50 kV and 1.1A. The resonator B-field of 1.18 Tesla is close to the limit of conventional magnet technology.
- The efficiency of the second harmonic cylindrical gyrotron is with 30% still high. It would require 50 kV and 1.33A for the electron beam. The low magnetic field of 0.59 Tesla is a major advantage.
- The first harmonic quasi-optical gyrotron shows only 20% electronic efficiency. By using a depressed collector, this value might be raised to 30%, reducing the requirements for the beam power supply to about 30 kV and 2A. The more complex cross bore magnet for the quasi-optical gyrotron could be a problem at the required field level of 1.18 Tesla. However, a superconducting magnet should also be taken into account.
- The second harmonic quasi-optical gyrotron yields the lowest electronic efficiency, but could be increased to about 16% by a depressed collector. The beam would require 30 kV and 2.5 A. The low magnetic field allows a compact design. The very high cavity Q of 100 000 is favourable with respect to load sensitivity.

For power transmission from the gyrotron to the ECRIS three different lines are considered: A TE_{01} -waveguide, a HE_{11} -waveguide and TEM_{00} -beam guide. The HE_{11} line has the lowest transmission losses, whereas the TEM_{00} line allows to focus the microwave beam through a small entry port into the ion source.

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