From Series Production of Gyrotrons for W7-X Towards EU-1 MW Gyrotrons for ITER

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***Abstract*—Europe is devoting significant joint efforts to develop and to manufacture MW-level gyrotrons for electron cyclotron heating and current drive of future plasma experiments. The two most important ones are the stellarator Wendelstein W7-X at Greifswald and the tokamak ITER at Cadarache. While the series production of the 140 GHz, 1 MW, CW gyrotrons for the 10 MW ECRH system of stellarator W7-X is proceeding, the European GYrotron Consortium (EGYC) is presently developing the EU-1 MW, 170 GHz, CW gyrotron for ITER. The initial design had already been initiated in 2007, as a risk mitigation measure during the development of the advanced ITER EU-2 MW coaxial-cavity gyrotron. The target of the ITER EU-1 MW conventional-cavity design is to benefit as much as possible from the experiences made during the development and series production of the W7-X gyrotron and of the experiences gained from the earlier EU-2 MW coaxial-cavity gyrotron design. Hence, the similarity of the construction will be made visible in the present article. During 2012, the scientific design of the ITER EU-1 MW gyrotron components has been finalized. In collaboration with the industrial partner Thales Electron Devices (TED), Vélizy, France, the industrial design of the technological parts of the gyrotron is being completed. A short-pulse prototype is under development to support the design of the CW prototype tube. The technological path towards the EU ITER-1MW gyrotron and the final design will be presented.**

***Index Terms*—Plasma heating, microwave generation, gyrotrons, stellarators, tokamaks**

I. INTRODUCTION

TWO major plasma fusion devices are under construction in Europe, the stellarator Wendelstein W7-X at Greifswald, Germany [1] and the international tokamak ITER at Cadarache, France [2]. Both experiments are relying on electron cyclotron resonance heating (ECRH) as the main heating method for steady state operation, while in addition it is planned for ITER to apply electron cyclotron resonance technique for current drive (ECCD). ECRH & ECCD offer the compatibility to the various physics demands, such as controlled plasma start-up, steady state plasma control, and performance optimization by plasma profile shaping. It offers excellent coupling to the plasma, remote launching and very good localization of the absorbed power.

The construction of the stellarator W7-X is almost completed and the device is approaching the commissioning phase [3]. W7-X operation will be supported by a 10 MW continuous wave ECRH system working at 140 GHz in 2nd harmonic X- or O-mode. To date, the ECRH-system of W7-X is in stand-by with already 5 out of 10 gyrotrons operational. The series production of the W7-X 1 MW, CW gyrotrons [4,5] for the 10 MW ECRH system is proceeding.

The European gyrotron development for ITER started with an advanced 170 GHz, 2 MW coaxial-cavity design. RF tests with an industrial CW prototype were done at the European test facility at EPFL-CRPP Lausanne in December 2011 [6]. The prototype did show an excellent voltage stand-off. It was directly possible to excite the nominal operating $TE_{34,19}$-mode. The output RF-beam intensity was in good agreement with the expected one. Without further optimization, the RF output power reached the level of almost 2.1 MW in short-pulse (1 ms) operation with single-stage depressed collector (SDC) achieving 46 % efficiency. However, due to a fatal internal water leak during the initial operation of the prototype, and, in

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view of the limited development time available, the EU gyrotron development strategy for ITER shifted to the 1 MW back-up proposal, which had already been initiated in 2007, the EU-1 MW $TE_{32,9}$-mode conventional cavity design. Presently, the European GYrotron Consortium (EGYC) has finalized the design of the first prototype. It includes the scientific design of all key components, namely the magnetron injection gun (MIG), the beam tunnel, the cavity, the quasi-optical output system (Q.-O. system) and the single-stage depressed collector (SDC). In addition, in collaboration with the industrial partner TED, the industrial design of the gyrotron is being completed.

The ITER EU-1 MW gyrotron development relies on the similarity to the W7-X construction of the key components. It will allow the start of the series production after having produced one single CW prototype. That prototype needs to fulfill the main ITER requirements in terms of RF output power, efficiency, RF-beam quality and pulse length. Therefore, an additional short-pulse prototype shall help to validate the basic performance parameters including the scientific design of the key components of the EU-1 MW CW prototype. Its modular design will allow quick modifications of the key components during the final design and validation phases of the CW prototype. Both, the short-pulse prototype and the CW prototype shall be tested at the EU gyrotron test facilities at KIT, Karlsruhe, Germany and at EPFL-CRPP Lausanne, Switzerland. Main test campaigns on the short pulse gyrotron will take place at the KIT test facility (using an existing Oxford Instruments (OI) superconducting magnet (SCM)) which has been upgraded with a normal conducting coil. The maximum magnetic field of this magnet is about 6.72 T (6.87 T with NC-coil) and the bore hole diameter is about 275 mm. Long-pulse tests are planned to be performed mostly at the EPFL-CRPP test facility (using a new liquid He-free SCM).

II. GYROTRON DESIGN

In this chapter the scientific designs of the key components for the ITER EU-1 MW gyrotron are presented.

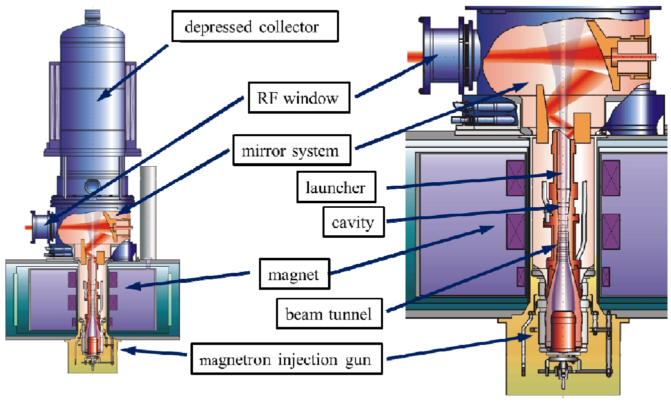

Fig. 1. 3D sketch of the W7-X conventional-cavity gyrotron mounted in the KIT gyrotron magnet (OI). The basic construction is similar to the ITER EU-1 MW gyrotron. Main components of the gyrotron are highlighted.

Fig. 1 shows a sketch of the W7-X gyrotron, whose basic construction is close to the ITER gyrotron. The different key components of the gyrotron are highlighted.

A. Magnetron Injection Gun (MIG)

The magnetron injection gun of the EU-1 MW 170 GHz gyrotron bases on a diode electron gun design, which is similar to that used in the W7-X gyrotron. The parametric technique introduced in [7] was used for the optimization of the MIG design using the electron optics codes *Ariadne* [8] and *ESRAY*. A very low spread in transverse velocity has been achieved as it is shown in the Table I.

TABLE I
PARAMETERS OF THE BEAM AT THE CAVITY INPUT

Parameters	**Startup**	**Neutralized**
Radius	9.44 mm	
Thickness	0.326 mm	0.326 mm
Pitch angle α	1.46	1.29
Transverse velocity spread	1.3 %	1.1 %
Accelerating voltage	79.5 kV	
Beam voltage	73.3 kV	79.5 kV

The beam voltage is defined as the accelerating voltage minus the voltage depression due to beam space charge. In case of neutralization a complete compensation of the voltage depression has been assumed.

Additional criteria have been applied in order to suppress trapped electrons in the MIG and to limit the harmful beam halo current. As a result the final design is not showing any potential well, in particular at the rear part of the MIG, while the electrons which are emitted by the cathode surface with zero velocity and which could contribute to the generation of the beam halo current are not magnetically trapped [9, 10]. However, this might not be correct for secondary electrons emitted from the surface.

B. Beam Tunnel

The beam tunnel is designed very closely to the W7-X beam tunnel. It consists of an alternative stack of copper and attenuating ceramic (BeO/SiC) rings (see Fig. 2). The ceramic rings attenuate unwanted modes, thereby lowering the quality factor in order to increase the starting current of possible unwanted oscillations.

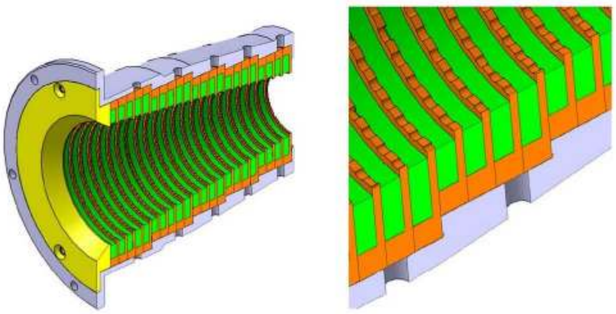

Fig. 2. Beam tunnel structure of the ITER gyrotron. The corrugations in the copper rings are shown in more detail.

Due to the low surface currents of the azimuthally symmetric $TE_{0,n}$-modes on the surface of the beam tunnel, an additional technique is employed for their suppression [11].

The azimuthal symmetry of the beam tunnel is broken by introducing irregular indentations on the copper rings. The width and periodicity of the λ/4-corrugations are varied. Together with the monotonically decreasing inner diameter of the adjacent rings, this geometry represents a structure that avoids longitudinal periodicity.

C. *Interaction Cavity*

The $TE_{32,9}$-mode has been selected as the cavity operating mode for the EU-1 MW gyrotron. Similar behavior as for the W7-X gyrotron has been considered as the major requirement during the selection process, which is valid for mode competition and stability in particular [12]. Fig. 3 shows the axial profiles of the cavity and the non-linear up-taper, as well as the axial profile of the static magnetic field.

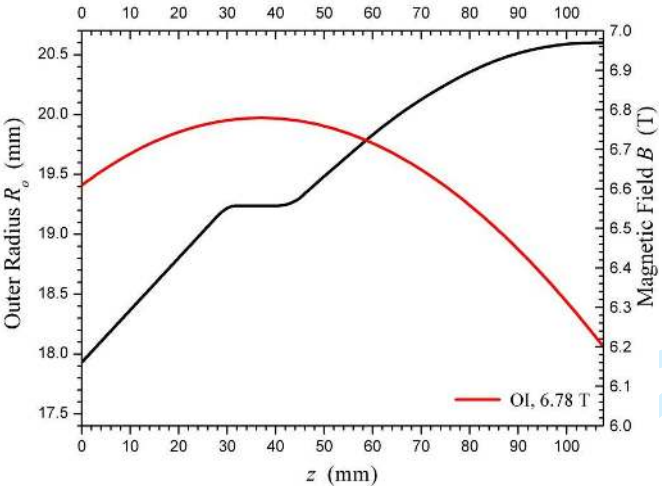

Fig. 3. Axial profile of the ITER $TE_{32,9}$-mode cavity and the up-taper. The profile of the static magnetic field considered in the design is added also.

All three available EU numerical interaction codes (SELFT, EURIDICE and COAXIAL) have been used for the optimization of the cavity geometry and the final verification of the performance.

TABLE II
BASIC OPERATION AND CALCULATED PERFORMANCE PARAMETERS OF THE ITER EU-1 MW GYROTRON

Cavity magnetic field B_o	6.78 T
Accelerating voltage V_c	79.5 kV
Beam current I_b	40.0 (45.0) A
Beam radius R_b	9.44 mm
Electron velocity ratio α	1.3
Output power at RF window	1.0 (1.14) MW
Operating frequency (cold cavity)	170.23 GHz
Efficiency (without SDC)	31.4 %
Peak ohmic wall loading ($\sigma = 1.4 \times 10^7$ S/m)	2.4 (2.7) kW/cm^2

Table II shows the fundamental operating parameters considered in the simulation for the $TE_{32,9}$-gyrotron and the final simulated output power and efficiency.

In long pulse operation, assuming full space charge neutralization (i.e. 79.5 keV beam energy), the expected RF output power generated by the electron beam at nominal operating parameters is calculated to be 1.12 MW, which corresponds to 35 % electronic efficiency. After subtracting all the anticipated losses (i.e. Ohmic losses, stray-radiation losses, window losses), an available RF output power of 1.02 MW can be expected at the gyrotron window. The overall efficiency without single-stage depressed collector (SDC) is > 31 %. An RF output power of 1.14 MW at the window (corresponding to 1.25 MW of generated power) will be possible with very similar efficiency, if the tube is operated at an increased beam current of 45 A. Based on that results, it is expected to have a proper operational margin, which will lead to an output power of min. 1 MW at long-pulse operation.

Regarding short-pulse operation (non-neutralized case), slightly changed operating parameters of the magnetic field and use of higher acceleration voltage ($V_c \sim 85$ kV) to compensate for the voltage depression due to the beam space charge, are leading to very similar simulated RF performance.

Fig. 4 shows the calculated electronic efficiency and maximum Ohmic wall losses in the cavity for the $TE_{32,9}$-gyrotron, which have been derived from the self-consistent interaction calculations. To cope with the high Ohmic wall loading is a key issue of the tube development.

A simple linear model for the space charge neutralization of the electron beam is assumed in the simulation (in the spirit of [13]), which allows the study of the principal behavior during neutralization. Fig. 4 shows the assumed beam voltage which is the input for the simulation during all three different operating states of the gyrotron: start-up, neutralization and final steady-state (neutralized case). In the simulation, it is assumed that full space-charge neutralization in the cavity is achieved at long-pulse operation. During start-up, the beam voltage V_b (beam energy) increases linearly with the accelerating voltage V_c. At $t = t_1$, when the accelerating voltage reaches its nominal value ($V_c = 79.5$ kV), the beam voltage reaches the level of approx. $V_b = 73.5$ kV. This difference (~6 kV) between V_c and V_b is the voltage depression due to the beam space charge. Then, a stable operating point is achieved (simulation time frame: $t = t_1$ to $t = t_2$). At $t = t_2$, the simulation of the neutralization phase begins and full neutralization is achieved at $t = t_3$, where $V_b = V_c = 79.5$ kV. Again, it is assumed that the beam energy is increasing linearly to its final value. This is a very basic linear model for the beam neutralization; nevertheless, it allows the examination of the principle behavior during the neutralization phase. The final neutralization effect in the gyrotron will have to be verified in the experiment. It is understood that the neutralization of a gyrotron depends on various different parameters [14].

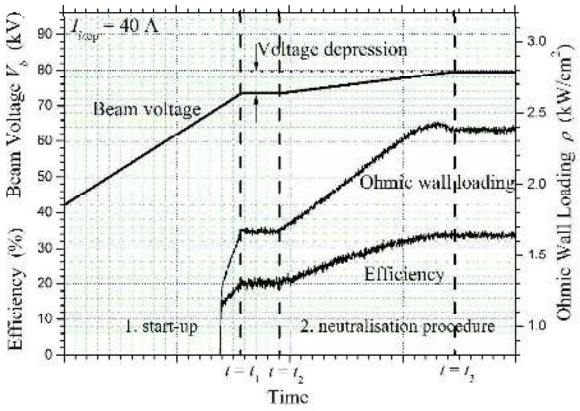

Fig. 4. Beam voltage, electronic efficiency and maximum Ohmic wall loading (for the $TE_{32,9}$ mode) versus time.

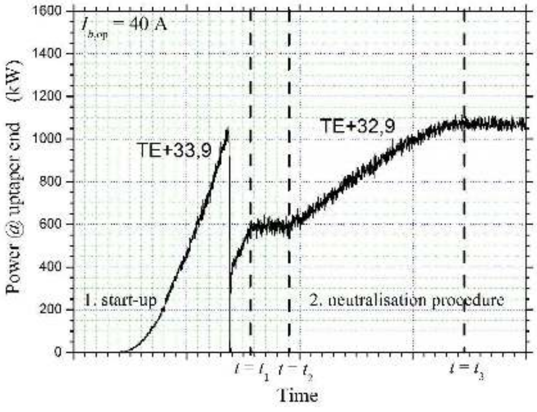

Fig. 5. Simulated RF output power and mode competition versus time. The simulations have been performed with the magnetic field optimized for the neutralized case.

During startup, the $TE_{33,9}$-mode is excited first as shown in Fig. 5. When the beam voltage reaches a minimum level of approx. V_b = 70 kV the nominal $TE_{32,9}$-mode dominates. Fig. 5 shows also the calculated transient of the RF output power until the gyrotron reaches its neutralized state ($t = t_3$). At this point the gyrotron achieves the full performance for the given nominal operating parameters.

D. *Quasi-Optical Mode Converter*

The quasi-optical mode converter in the gyrotron is transforming the $TE_{32,9}$-mode into a fundamental Gaussian wave beam. The quasi-optical mode converter consists of a launcher and an additional mirror system [15, 16]. The launcher is numerically optimized using the method proposed in [17]. The mirror system consists of three mirrors. The first mirror is a quasi-elliptical one, the second and third ones are beam-shaping mirrors, which are used to change the beam parameters, such as the beam waists and the positions of the focusing planes according to the requirement. The field distribution in the mode converter has been analyzed, the simulation results show that the fundamental Gaussian mode content of the wave beam is approximately 98.6 % in the window plane. A numerical estimation of the stray radiation results in 1.75 % stray losses, as it is calculated using the commercial 3-D full-wave vector analysis code SURF3D. The profile of the RF beam at the window plane of the output window is shown in Fig. 6 and Fig. 7.

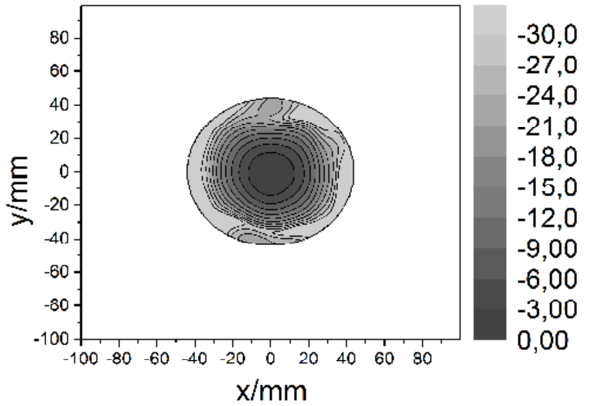

Fig. 6. Amplitude (in dB) distribution of the Gaussian mode at the window plane.

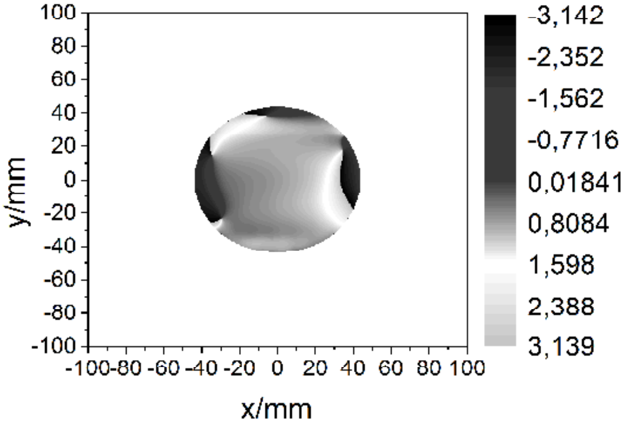

Fig. 7. Phase (in radian) pattern of the Gaussian mode at the window plane.

The main difference between the launcher of the ITER tube and the one used in W7-X is the definition of the inner surface. The inner surface of the W7-X launcher is helically deformed. Fig. 8 is showing the contour of that launcher.

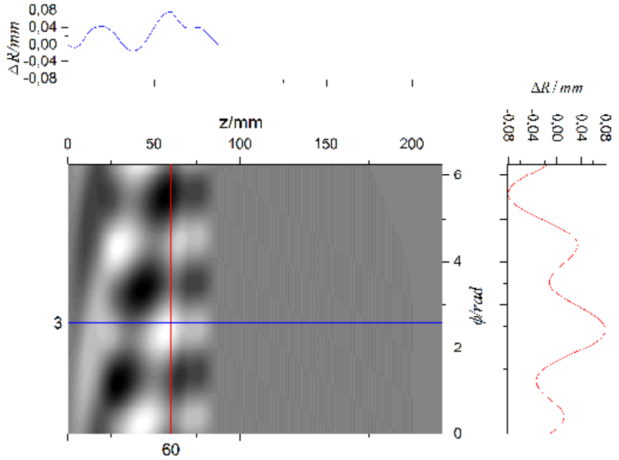

Fig. 8. Inner surface of the launcher for the W7-X gyrotron.

The launcher for the ITER gyrotron is a mirror-line type launcher. Fig. 9 is showing the newly designed contour.

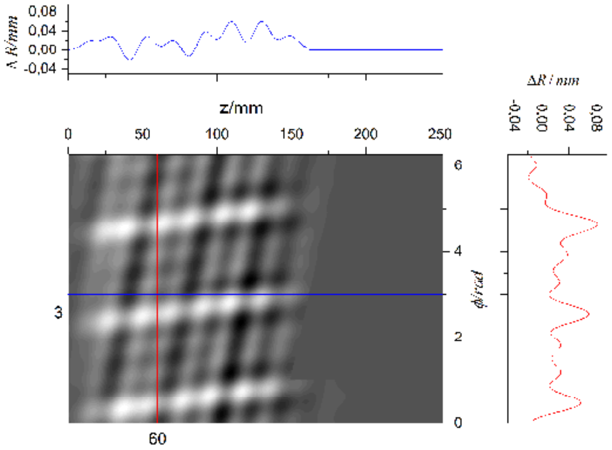

Fig. 9. Inner surface of the launcher for the $TE_{32,9}$-mode gyrotron.

A comparison of Fig. 8 and Fig. 9 shows that the maximum amplitude of the perturbation is very similar to the W7-X launcher, whereas the frequency of the deformation is higher. A helically deformed launcher for the TE32,9-mode ITER gyrotron has also been numerically studied during the design phase. The corresponding simulation results have shown that the Gaussian mode content is approximately 3% lower and the diffraction loss of the launcher is about 0.48% higher in comparison to a mirror-line type launcher. Hence, the mirror-line type launcher for the ITER gyrotron can provide an RF beam with higher Gaussian mode content and a lower stray radiation.

E. Collector

The geometry of the collector is identical to the W7-X gyrotron, which is shown in Fig. 10. It consists of a cooled copper section in which the energy of the spent electron beam is loaded, and another stainless steel (SS) section between the mirror box and the copper section of the collector. The cooling system of the collector is based on the hypervapotron technique. The operation of the collector has been validated for the energy distribution of the spent beam. For this purpose the COLSIM code has been used. According to simulation the maximum power loading on the collector wall is expected to be less than 0.5 kW/cm^2.

As for W7-X, two types of sweeping schemes have been numerically evaluated: (i) the axial and (ii) the transversal scheme. The axial sweeping system bases on the periodic variation of the axisymmetric magnetic field in order to sweep the spent beam energy along the copper section of the collector. The variation of the magnetic field is achieved by a cylindrical coil, which is placed along the copper section of the collector. The applied AC current on the coil causes an axial magnetic field periodically modifying the beam electron trajectories in the collector regions. However, the operation of the axial sweeping system is limited to sweeping with frequencies less than 10 Hz, due to the eddy currents in the copper of the collector.

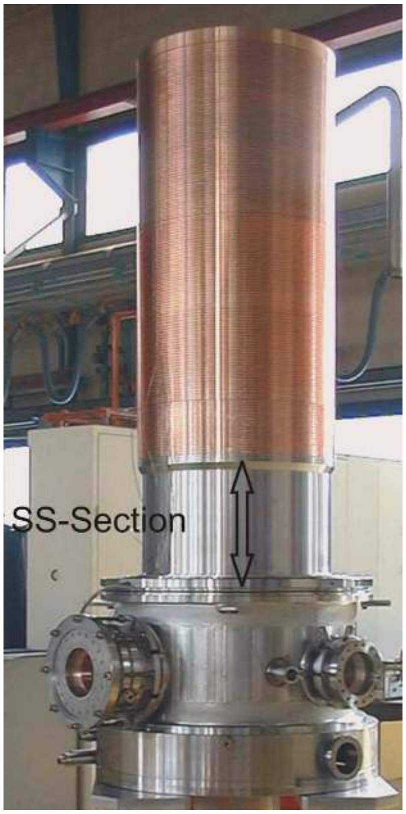

Fig. 10. The collector of the W7-X gyrotron. The collector is subdivided into two sections: (i) the copper section (CS) at top, and (ii) the stainless steel section (SS) at the base of the collector.

The transversal sweeping system is based on the generation of a rotating transversal magnetic field at the stainless steel section of the collector [18]. This is achieved by placing a set of six coils around the collector, having their axes perpendicular to the gyrotron axis of symmetry. The geometry of the sweeping coils is shown in Fig. 11.

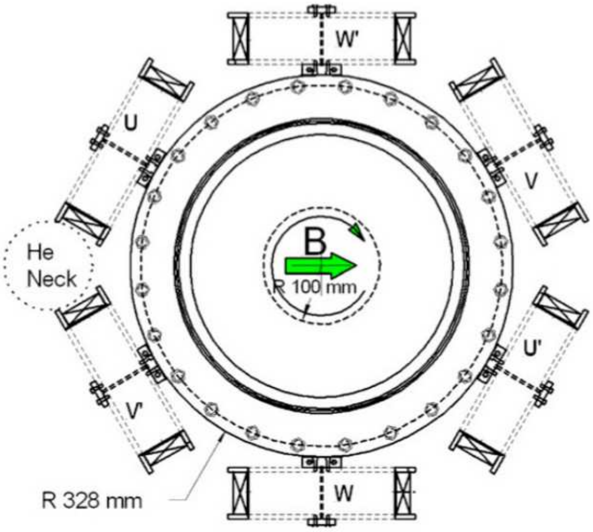

Fig. 11. The transverse magnetic field is produced by six coils which surround the SS-section of the collector.

The phase difference of the AC currents of two neighboring coils is 60 degree. As a result, the electron trajectories are periodically modified, distributing the energy of the spent beam on a larger collector area. The eddy currents in the stainless steel section of the gyrotron are significantly smaller than in the copper section. Therefore, a much higher sweeping frequency (50 Hz) can be used.

III. SHORT-PULSE GYROTRON

The short-pulse prototype is a risk mitigation action to secure the development of the CW prototype. Therefore, the geometry of all critical gyrotron components ought to be identical to the CW prototype except for the external cooling circuit. However, the final structure of the components is significantly simpler, due to the fact that no specific cooling is required for all components except for the collector and the magnetron injection gun.

The collector cooling system remains simple, since the pulse lengths will be limited to below 10 ms. In particular, a simple water cooling structure will be applied in order to keep the duty cycle as high as possible. On the other hand, the MIG will get an oil-cooling similar to the CW prototype. It will allow to dissipate the heat generated by the emitter ring. Vacuum-tight flanges will be used for all connections. That offers the flexibility to change parts in case of further improvements of the design, if advisable.

The following targets are set for tests of the short pulse prototype:

- The electron beam quality will be checked in the non-neutralized phase, e.g. regarding trapped electrons.
- The excitation and stable operation of the main operating $TE_{32,9}$-mode will be checked.
- The presence of parasitic oscillations in the beam tunnel and uptaper (ACI) will be checked.
- The development of the RF output power during the startup phase will be measured and compared to the calculated output power from the numerical codes.
- The operational margin will be tested by increasing the beam current and/or the beam energy above the ITER specifications.
- The maximum efficiency with and without depressed collector during the startup will be measured.
- The limit of the collector depression voltage will be investigated.
- The beam waist and the Gaussian mode content of the output beam will be measured.
- The internal stray radiation losses will be measured.
- The voltage standoff in the steady state will be checked with and without the nominal magnetic field.

IV. SUMMARY

Europe is devoting significant joint efforts in the development of gyrotrons for future fusion applications. Especially in view of the changes in the ITER EU gyrotron development strategy, the progress in the EU development of fusion gyrotrons for ITER is of vital interest to the fusion community. In this context the present report shows the design strategy by describing the development status of the ITER EU-1 MW gyrotron in detail. The similarity to the W7-X gyrotron is highlighted. As the manufacturing of a short-pulse prototype is seen as vital for a successful CW gyrotron development, the similarities and targets of the CW prototype and the short-pulse prototype are presented.

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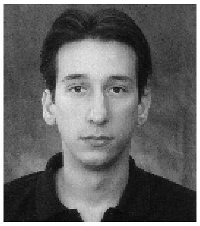

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Francois Legrand, photograph and biography not available at the time of publication

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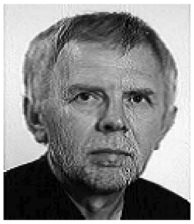

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Manfred Thumm (SM'94-F'02) was born in Magdeburg, Germany, on August 5, 1943. He received the Dipl. Phys. and Dr. rer. nat. degrees in physics from University of Tübingen, Germany, in 1972 and 1976, respectively.

At the University of Tübingen he was involved in the investigation of spin-dependent nuclear forces in inelastic neutron scattering. From 1972 to 1975 he was Doctoral Fellow of the Studienstiftung des deutschen Volkes. In 1976 he joined the Institute for Plasma Research in the Electrical Engineering Department of the University of Stuttgart, Germany, where he worked on RF production and RF heating of toroidal pinch plasmas for thermonuclear fusion research. From 1982 to 1990 his research activities were mainly devoted to electromagnetic theory and experimental verification in the areas of component development transmission of very high power millimeter waves through overmoded waveguides and of antenna structures for RF plasma heating with microwaves. In June 1990 he became a Full Professor at the Institute for Microwaves and Electronics of the University of Karlsruhe, Germany, and Head of the Gyrotron Development and Microwave Technology Division, Institute for Technical Physics, Research Center Karlsruhe (Forschungszentrum Karlsruhe: FZK). From April 1999 to September 2011, he was the Director of the Institute for Pulsed Power and Microwave Technology, FZK, where his current research projects have been the development of high power gyrotrons, dielectric vacuum windows, transmission lines and antennas for nuclear fusion plasma heating, and industrial material processing. On October 1, 2009, the University of Karlsruhe and the FZK have merged to the Karlsruhe Institute of Technology (KIT). M. Thumm has authored/co-authored 6 books, 18 book chapters, 290 research papers in scientific journals, and more than 1270 conference proceedings articles. He holds 12 patents on active and passive microwave devices.

He is member of the IEEE EDS Vacuum Devices Technical Committee and the NPSS PSAC Executive Committee, a member of the Chapter 8.6 Committee Vacuum Electronics and Displays of the Information Technical Society in German VDE (Chairman from 1996 to 1999) and a member of the German Physical Society. From 2007 to 2008 he was an EU member of the ITER Working Group on Heating and Current Drive, the vice chairman of the Scientific-Technical Council of the FZK and the vice chairman of the Founding Senate of the KIT. From 2008 to 2010 he was the deputy head of the Topic Fusion Technology of the KIT Energy. He was the General Chair of the IRMMW-THz 2004 and IEEE ICOPS 2008 Conference in Karlsruhe, Germany. He has been a member of the International Organization and Advisory Committees of many International Conferences and a member of the Editorial Boards of several ISI refereed journals. From 2003 to 2010 he was the ombudsman for upholding good scientific practice at FZK/KIT. Since 2012 he has been Associate Editor for Vacuum Electronics Devices for IEEE Trans. Electron Devices and Distinguished Lecturer of IEEE NPSS and since 2013 Distinguished Scientist of KIT.

He was awarded with the Kenneth John Button Medal and Prize 2000, in recognition of outstanding contributions to research on the physics of gyrotrons and their applications. In 2002, he was awarded the title of Honorary Doctor, presented by the St. Petersburg State Technical University, for his outstanding contributions to the development and applications of vacuum electron devices. He received the IEEE-EDS 2008 IVEC Award for Excellence in Vacuum Electronics for outstanding achievements in the development of gyrotron oscillators, microwave mode converters and transmission line components, and their applications in thermonuclear fusion plasma heating and materials processing. Together with two of his colleagues he received the 2006 Best Paper Award of the Journal of Microwave Power and Electromagnetic Energy and the 2009 CST University Publication Award. In 2010 he was awarded with the IEEE-NPSS Plasma Science and Applications Award for outstanding contributions to the development of high power microwave sources (in particular gyrotrons) for application in magnetically confined fusion plasma devices as well as for stimulation and establishing of extensive international co-operations. He is a winner of the 2010 open grant competition of the Government of the Russian Federation to support scientific research projects implemented under supervision of Leading Scientists at Russian institutions of higher education. Together with A. Litvak and K. Sakamoto he has been the recipient of the EPS Plasma Physics Innovation Prize 2011 for outstanding contributions to the realization of high power gyrotrons for multi-megawatt long-pulse electron cyclotron heating and current drive in magnetic confinement nuclear fusion plasma devices. In 2012 he was awarded with the Heinrich Hertz Prize of the EnBW Foundation and the KIT for outstanding contributions to generation, transmission and mode conversion of high and very high microwave power for nuclear fusion and the HECTOR School Teaching Award in Embedded Systems Engineering.

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Minh Quang Tran received his PhD from the Swiss Federal Institute of Technology in Lausanne (EPFL), Switzerland. At the Centre for Plasma Physics Research (CRPP) of the EPFL, he initiated the development of gyrotron and the use of electron cyclotron wave to heat and drive current in tokamak plasma. Gyrotron development is one of his main scientific research interest. Prof M. Q. Tran is currently General Director of the CRPP and is member or chair of many international scientific and advisory committees.

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