Numerical Investigation on Spent Beam Deceleration Schemes for Depressed Collector of a High Power Gyrotron

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***Abstract*—Single stage depressed collector systems are widely used in high power gyrotrons in order to increase the overall efficiency. The position where the deceleration of the beam takes place influences the collector efficiency. In this work, several deceleration schemes are numerically investigated for the short pulse prototype of the 170 GHz, 1 MW European gyrotron for ITER. The results of this work are in a qualitative agreement with the results of dedicated experiments. A simple idea is also proposed for the significant increase of the overall gyrotron efficiency without an important technological modification.**

I. Introduction

The idea of the application of a retarding voltage for the deceleration of the electron spent beam is widely used in high power gyrotrons for the increase of the overall efficiency for the last two decades [1]–[3]. The spent beam deceleration usually takes place either at the entrance of the electron beam in the mirror box (after the end of the quasi-optical launcher), as it is the case for the 140 GHz 1 MW gyrotron for Wendelstein W7-X [4] and the European (EU) 170 GHz, 1 MW conventional cavity gyrotron for ITER [5], [6], or at the entrance of the beam in the collector, as it is the case for the 170 GHz, 1 MW Russian gyrotron for ITER [7], [8] and the European 170 GHz 2 MW coaxial cavity gyrotron [9], [10].

The position of the beam deceleration has a strong impact on the overall gyrotron efficiency due to the influence of the space charge voltage depression of the electron beam. Even if the second approach is more efficient for gyrotron operation, as it is presented in Sec. II, the first approach is more attractive for technological and practical reasons. Many manufacturing difficulties and gyrotron robustness issues are correlated to the large size of the fragile ceramic used in the second approach in which the isolation placed at the bottom of the large collector. In addition, the fact that a high voltage is applied on the mirror box causes several additional complexities: (i) isolation is necessary between the gyrotron and the grounded magnet, (ii) a DC break is required at the connection between the window and the waveguide at the output, (iii) several difficulties occur at the installation and operation of a transverse sweeping system due to the fact that the coils are in close vicinity with high voltage components, (iv) the ion getter pumps are installed on the collector, further away from the magnetron injection gun (MIG), where a high quality vacuum is required. Furthermore, the position of the isolation ceramic at the bottom of the collector increases the risk of overheating from the stray radiation and a special cover must be used for its protection. Finally, the fact that a significant part of the gyrotron is at a high voltage in open air causes some security issues which is not the case in the first approach where all high voltage components are placed inside bore hole of the magnet which is usually filled with oil.

Due to all these reasons, the first approach for the spent beam deceleration was chosen for the collector of the EU gyrotron for ITER. Furthermore, an important design specification of that gyrotron was the technological similarity to the W7-X gyrotron in order to take advantage of the important experience gained on the specific technology during the many years of development of the series production tubes for the Wendelstein stellarator. Any discussion for modifications of the isolation ceramic position in the EU ITER gyrotron design would have caused an important technological modification which was out of the initial specifications and strategy.

In the context of the EU gyrotron development for ITER two prototypes have been manufactured: (i) the short pulse (SP) tube, manufactured at Karlsruhe Institute of Technology (KIT) [11] and (ii) the continuous wave (CW) industrial gyrotron [12], manufactured by Thales Electron Device (TED). The SP prototype is a simplified version of the industrial prototype with the purpose to validate the design of the main gyrotron subcomponents, such as the electron gun, beam tunnel, cavity and quasi-optical output coupler with a pulse length up to 10 ms. Oil cooling is applied at the electron gun similar to the industrial tube, while some water cooling is applied at the collector in order to increase the duty cycle. An important characteristic of the SP prototype is the modularity which provides us the possibility to easily exchange and test different subcomponents. The SP prototype was used in order to experimentally test the different deceleration schemes.

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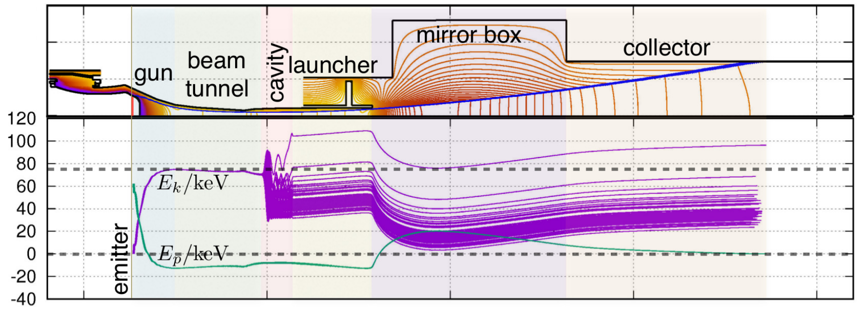


Fig. 1. Sketch of the SP prototype gyrotron shown at top while the kinetic E_k and the potential E_p energy of the beam electrons as a function of the axial position are plotted at the bottom.

A sketch of the SP prototype design, the electron beam and the equipotential lines are shown at the top of Fig. 1 while the kinetic and the potential energy of the electrons as a function of the their axial position are presented at the bottom of Fig. 1 as they are numerically calculated using the full gyrotron simulation approach [13]. The beam electrons are emitted from the heated emitter ring, are accelerated in the gun region and then are guided through the beam tunnel to the cavity, where the interaction with the nominal cavity mode takes place. The majority of the electrons lose part of their kinetic energy which is transformed to microwave energy. The beam electrons leave the cavity with a significant energy spread as shown in Fig. 1. Then, the kinetic energy of the electrons is slightly increased until the end of the launcher. A strong deceleration of the beam electrons takes place during their entrance in the mirror box due to the influence of the retarding voltage and the space charge voltage depression. Later, the kinetic energy of the beam electrons is significantly increased again while they are approaching the collector wall.

Using the electron optic code *Ariadne* [14] it was possible to calculate the influence of the nominal cavity mode on the beam electrons and to estimate the beam properties along the complete gyrotron geometry. The nominal radio-frequency (RF) field at the cavity was calculated with the cavity interaction code *EURIDICE* [15]. In order to keep the simulation time short, axisymmetric simulation takes place by choosing an azimuthal angle of the gyrotron geometry based on the worst case scenario concerning the collector efficiency. For the nominal SP prototype design, the azimuthal angle at which no mirror parts of the quasi-optical system are present is chosen.

Several deceleration schemes are investigated for the SP prototype gyrotron. Both approaches concerning the position of the isolation ceramic are theoretically and experimentally studied. The results of this analysis are presented in Sec. II. In Sec. III, a simple approach is proposed in which keeping the isolation ceramic at the bottom (first approach) and therefore maintain the technological advantages discussed earlier, keep the collector efficiency at a fairly high level. In Sec. IV, the main results of this work are briefly discussed.

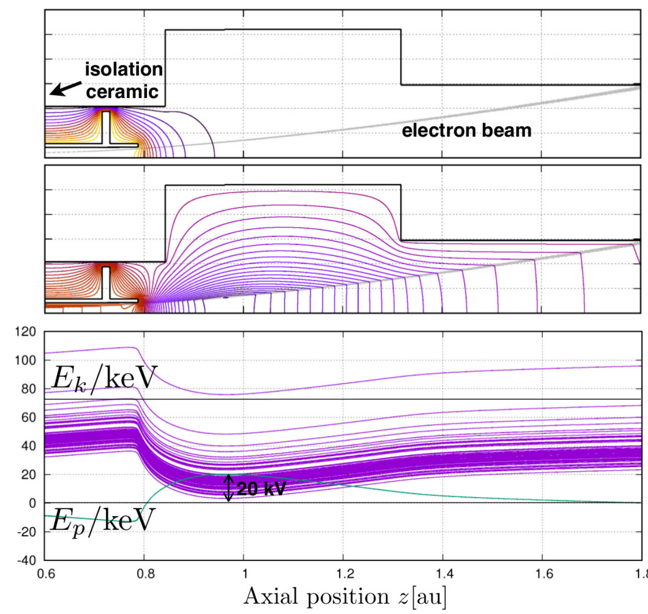
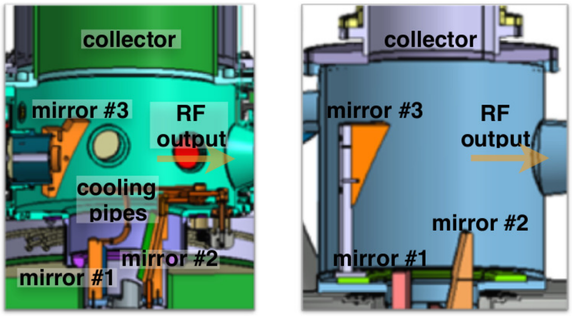


Fig. 2. The equipotential lines in the DS #1 for $I_b = 0$ A and $I_b = 45$ A are plotted at the top and middle respectively, while the potential and the kinetic energy for a large number of sample beam electrons as a function of the axial position are presented at the bottom.

II. Deceleration Schemes

The first deceleration scheme (DS #1) which has been investigated is the nominal design of the SP prototype gyrotron. In Fig. 2, the end of the launcher, the mirror box and the bottom part of the collector geometry are shown. The applied retarding voltage causes a deceleration of the electron beam at the entrance of the mirror box as is shown by the equipotential lines in the cases where the influence of the space charge of the spent beam is not taken into account ($I_b = 0$ A). The shape of the equipotential lines is dramatically modified under the influence of the beam space charge. The electron beam energy is strongly influenced by the additional deceleration at the entrance of the mirror box due to the space charge voltage depression. Then, the spent beam electrons are accelerated while they are approaching the grounded collector wall. The retarding voltage value was defined based on the criterion



a. CW prototype *b. SP prototype*

Fig. 3. Comparison of the CW with the SP prototype gyrotrons in the mirror box region.

Fig. 4. Dummy pipes installed in the SP prototype to emulate the cooling pipes in the industrial prototype.

that no spent beam electron is reflected back into the cavity. According to the simulation, the maximum retarding voltage is limited to only 14 kV. It is remarkable that the kinetic energy gain of electrons from the middle of the mirror box towards the collector is at the level of 20 keV. This significant amount of energy is transformed to heat on the collector walls. The theoretical overall efficiency of the gyrotron using this deceleration scheme is about 36 %.

According to the simulation, the presence of the cooling pipes at the mirror box of the industrial prototype, as shown in Fig. 3, contributes to a small increase of the efficiency. In order to investigate that experimentally in the SP prototype tube, a complex system of pipes, shown in Fig. 4, has been designed and manufactured in order to emulate the cooling pipes in the CW prototype. The numerical simulation results of this deceleration scheme (DS #2) are presented in Fig. 5. The presence of the cooling pipe at the anode voltage significantly modifies the shape of the equipotential lines and improves the operation of the single stage collector. The optimal applied retarding voltage is 23 kV, while the overall gyrotron efficiency increases to 42 %.

The third deceleration scheme (DS #3) concerns the replacement of the nominal SP prototype collector with the collector of the modular SP coaxial cavity gyrotron [10] in which the

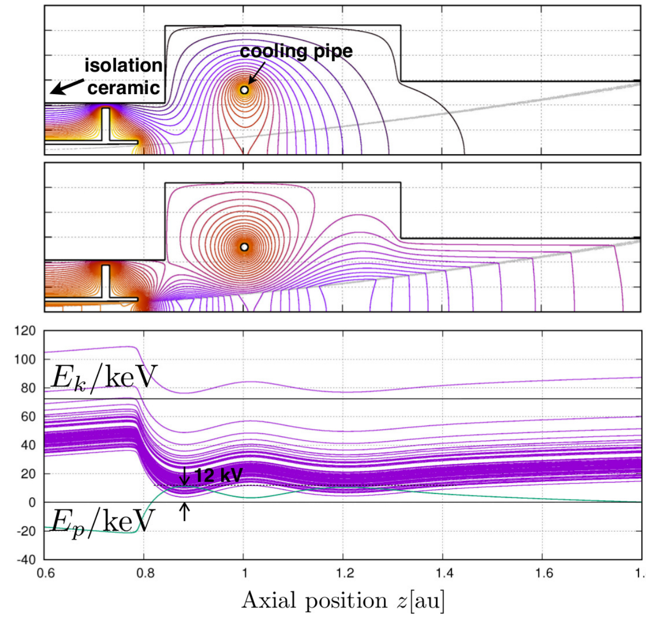


Fig. 5. The equipotential lines in the DS #2 for $I_b = 0$ A and $I_b = 45$ A are plotted at the top and middle respectively, while the potential and the kinetic energy for a large number of sample beam electrons as a function of the axial position are presented at the bottom.

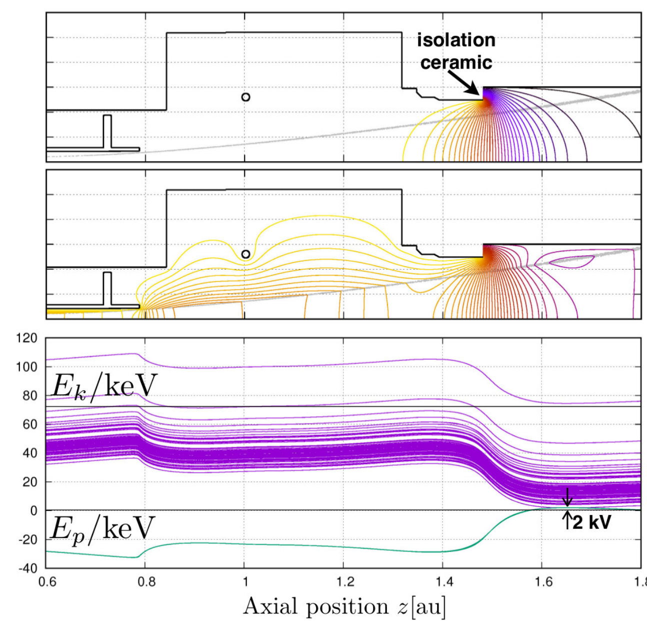


Fig. 6. The equipotential lines in the DS #3 for $I_b = 0$ A and $I_b = 45$ A are plotted at the top and middle respectively, while the potential and the kinetic energy for a large number of sample beam electrons as a function of the axial position are presented at the bottom.

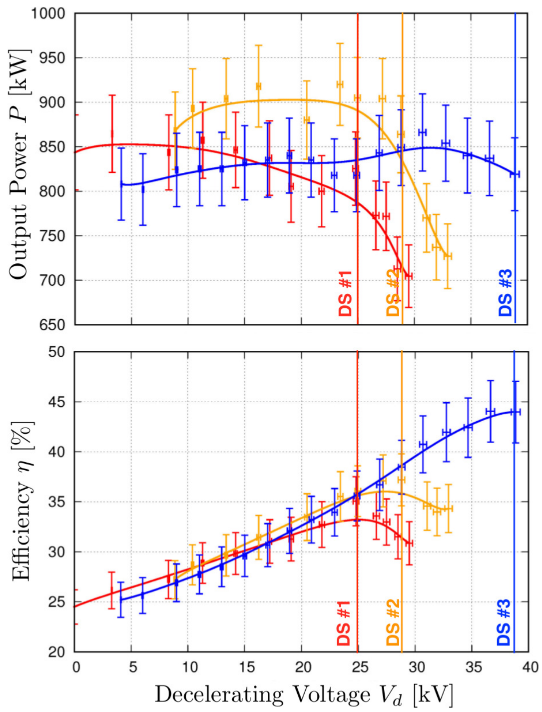


Fig. 7. Experimental comparison of output power (top) and overall efficiency (bottom) of the three different deceleration schemes.

isolation ceramic is placed at the bottom of the collector. In this way it was possible to test the approach in which the deceleration takes place at the bottom of the collector as shown in Fig. 6. A short circuit between the mirror box and the body structure was applied while an isolation ring replaced the metallic ring between the magnet and the gyrotron in order to isolate the grounded magnet from the mirror box on which a high voltage is applied. As it was expected, the applied retarding voltage and the gyrotron efficiency were significantly increased to 34 kV and 53 %, respectively. A small deceleration takes place at the entrance of the beam in the mirror box only due to the space charge voltage depression and the final deceleration takes place at the collector entrance mainly due to the applied decelerating voltage.

The three deceleration schemes also have been experimentally tested. The experimental results, shown in Fig. 7, are qualitatively in agreement with the theoretical expectations. The optimal decelerating voltages were measured as 25 kV, 28 kV, and 38 kV for DS #1, DS #2 and DS #3, respectively. For each decelerating scheme, the power is not significantly influenced for voltages smaller than the optimal decelerating voltage, while for higher values it is obviously decreased. Exception is the case DS #3, in which the limitation of 38 kV is related to the maximum possible applied voltage of the power supply used in the experiments and not to problems related to the reflected electrons. The overall gyrotron efficiency which was experimentally measured was 35 %, 37 % and 44 % for DS #1, DS #2 and DS #3, respectively. The significant quantitative difference in the efficiency between the experimental and the theoretical results is related to the fact than no the optimal accelerating voltage and beam current

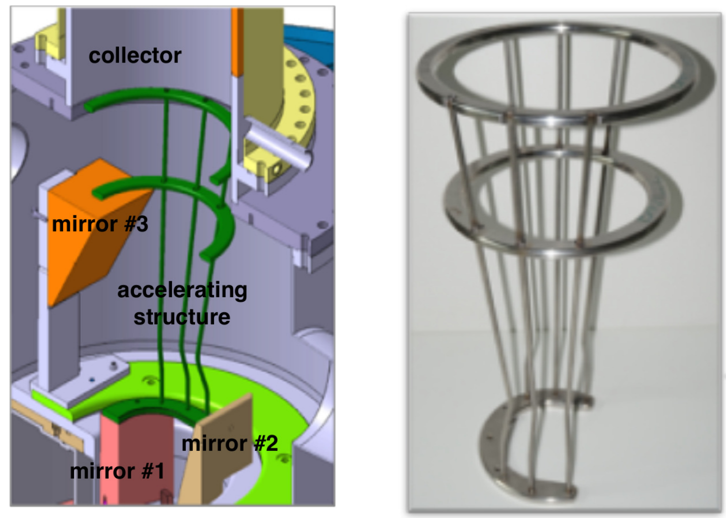


Fig. 8. 3D drawing of the accelerating structure installed in the SP prototype mirror box is presented at the left, while a photo of the accelerating structure is shown at the right.

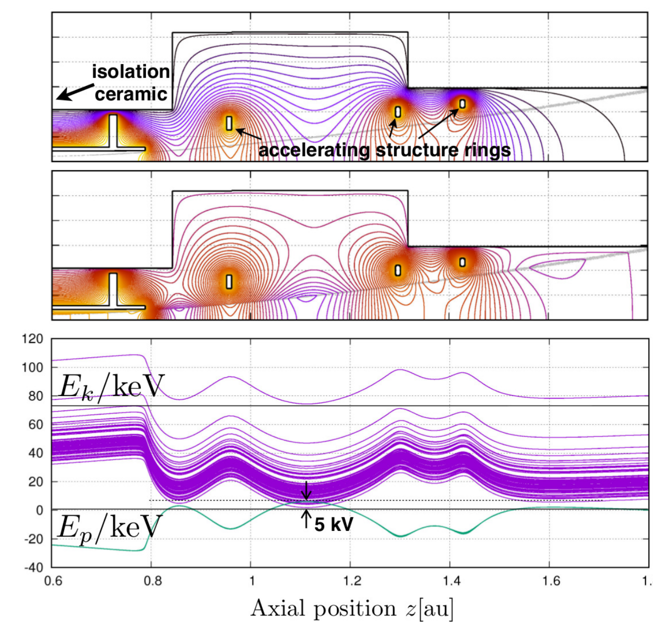


Fig. 9. The equipotential lines in the DS #4 for $I_b = 0$ A and $I_b = 45$ A are plotted at the top and middle respectively, while the potential and the kinetic energy for a large number of sample beam electrons as a function of the axial position are presented at the bottom.

were used in the experiments.

III. Accelerating Structure

The main outcomes of the numerical and experimental investigation of the three deceleration schemes presented in Sec. II are that the overall efficiency of the gyrotron was significantly better in DS #3, in which the deceleration takes place during the entrance of the beam in the collector, while it was possible to influence the efficiency by the presence of the dummy pipes (at DS #2), which emulate the cooling pipes of the industrial prototype. Based on these observations,

TABLE I
COMPARISON OF THE DECELERATING VOLTAGES AND GYROTRON EFFICIENCIES OF THE FOUR DIFFERENT DECELERATING SCHEMES.

Deceleration Scheme	Voltage V_d	Efficiency η
#1 (Nominal)	14 kV	36 %
#2 (CW prototype)	23 kV	42 %
#3 (Ceramic on top)	34 kV	53 %
#4 (Accelerating structure)	30 kV	49 %

an effort took place to design an internal structure with the goal to increase the efficiency of the SP prototype keeping the isolation ceramic at the lower part of the gyrotron.

Such a structure has been designed and it is shown at the left of Fig. 8. The aim of this structure is to keep the kinetic energy of the beam electrons at a high level until the collector entrance. It consists of three rings at three different axial positions. It is fixed on top of the mirror #1 which is at body voltage potential. Special attention took place to avoid any intersection of the geometry of the structure with the RF beam and to keep a safe distance between the rings and the electron beam. As is shown in Fig. 9, the presence of the rings in several axial positions keeps the influence of the beam space charge at low levels. In the worst case scenario concerning the azimuthal angle used in the axisymmetric simulation and applying the strict criterion of the slowest electron, the estimated retarding voltage is 30 kV and the overall gyrotron efficiency is 49 %.

A comparison of the decelerating voltages and the efficiency of the four different decelerating schemes is presented in Table I. It shows that even if the gyrotron performance with DS #4 is not as efficient as with DS #3, where the isolation ceramic is installed at the bottom of the collector, it is significantly improved in comparison with DS #1 and DS #2. Such a structure has been manufactured as shown in Fig. 8 (rignt). The construction of the acceleration structure is quite simple due to the fact that no cooling is needed for SP operation. The experimental tests of the SP prototype gyrotron using this structure are planned for the following months.

IV. CONCLUSION

Three different schemes were theoretically studied for the deceleration of the spent electron beam of the SP prototype gyrotron. The results of this analysis are qualitatively in agreement with the results of the experiments. The results indicate that the most efficient scheme is when the beam deceleration takes place at the entrance of the collector.

However, the installation of the isolation ceramic at the bottom of the collector causes several technological difficulties correlated with the robustness of the ceramic and the high voltage which must be applied to the mirror box. In order to overcome these issues, the deceleration of the beam at the collector entrance is achieved using an acceleration structure at body potential keeping the isolation ceramic at the bottom part of the gyrotron. It should be noted that the design of an acceleration structure dedicated for a CW tube would be more complicated due to the fact that cooling will be necessary due to the presence of the stray radiation in the mirror box.

The idea of the acceleration structure could be taken into account for a possible upgrade of the industrial tube of the 170 GHz, 1 MW, EU gyrotron for ITER. The major advantage of this idea is that no important technological modification of the gyrotron design is required while a significant gain of the overall efficiency is expected to be achieved.

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