Homogenous power distribution along gyrotron collector walls

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EC RF power sources will play a major role in the future operation of large scale tokamaks (ITER, DEMO). A 1MW/170GHz gyrotron is the standard RF power unit considered for ITER. Even though the efficiency of such devices has been significantly increased thanks to the depressed collector technique, the power deposited on the collector by the spent electron beam is still above 1MW. As a consequence, this power shall be spread along the collector walls to avoid overheating of the collector internal surface.

A novel solution, developed and tested at the Swiss Plasma Center (SPC), to flatten the power deposition profile is described in this paper. Based on an AM modulation of the vertical collector sweeping coil current, it allows for a more homogeneous power deposition profile and a substantial decrease of the peak load. This solution relies on a commercial off-the shelf (COTS) power supply and a common PLC controller, so it is a relevant solution for all MW-class gyrotrons presently in operation and for future applications.

Key words: Gyrotron, Sweeping, FPGA

1. Introduction

Electron cyclotron resonance heating (ECRH) systems employing high power gyrotrons are essential for Tokamaks and other large scale magnetic fusion plant. ITER, for instance, will be equipped with 24 gyrotrons operated in cw-mode each delivering 1MW of RF-power at the frequency of 170GHz and with a specified global efficiency higher than 50%. Hence, the power of the spent electron beam, that is to say the remaining power of the electrons incident on the collector after they have released part of their kinetic energy into the RF wave, is at least of 1MW or more if the 50% global efficiency is not reached. This power must be removed from the collector made of solid OFHC-copper.

The impact location on the collector of the spent electron beam is determined by the gyrotron physics, the magnetic field configuration defined by the superconducting (SC) coil and the collector geometry. Without a sweeping system in the collector region, the maximum power density of 500W/cm^2 would be largely exceeded and therefore overcome the thermomechanical limits of OFHC copper.

The standard technique to not overcome the maximum power density of 500W/cm^2 consists in a magnetic sweeping of the spent electron beam along the collector surface by superposing an AC magnetic field, generated by room temperature Cu-coils, onto the static field generated by the SC-coils. Prior to this work, two different solutions have been implemented: the traditional Vertical Field Sweep System (VFSS) and the Transverse Field Sweep System (TFSS) [1].

1.1. Vertical magnetic Field Sweep System (VFSS)

The most common method to spread the spent electron beam power along the collector wall is based on the VFSS principle. A solenoid surrounds the collector region and generates a magnetic field in the z axis. The concept consists of superposing an alternating magnetic field with an additional static component, over the stationary magnetic field created by the SC-coils magnet. The additional static field component is essential to adjust the strike point of the electrons at the middle of the collector region. Then, the alternating field deflects the electron beam along the z axis. The vertical sweeping influences the angle of incidence of the electron beam at the strike points. So, the power deposition at the highest part of the collector wall will be lower than at the lowest part, because the incidence is more tangential. This phenomenon occurs regardless the sweeping system strategy chosen. Figure 1 depict the collector region and the variation of the electron beam trajectory.

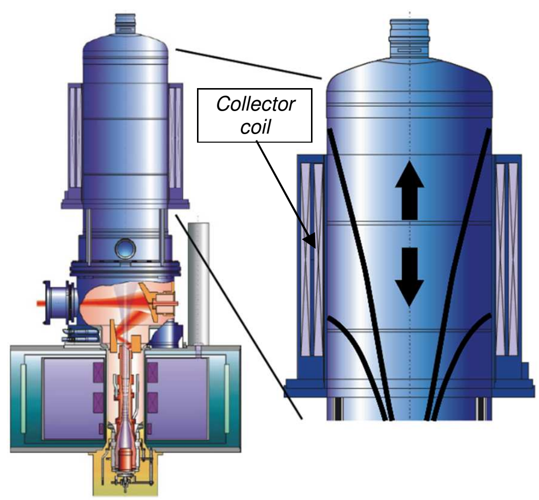

Fig. 1 Principle sketch of a VFSS [2]

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In order to distribute as homogeneously as possible, the amount of power over the collector surface, the ideal variation of the magnetic field along the vertical axis should be linear. A triangle waveform best characterizes the ideal vertical sweeping.

Nevertheless, one has to consider that the collector coil used to create the VFSS is situated outside the gyrotron collector. The magnetic field inside the collector is therefore influenced by the eddy currents which take place in the collector copper. Thus, the collector itself appears as a single-turn coil in short-circuit, acting as a low pass filter that dramatically reduces the dynamics of the system, definitively ruling out the possibility of having a fast variation of $B_z(t)$ inside the collector.

Most of the time, for low power gyrotrons, a low frequency sine current, typically 5-10Hz, is applied to the collector coil to allow the magnetic field to penetrate with the lowest attenuation possible inside the gyrotron. With a sinusoidal variation of the magnetic field, the time derivative of Bz(t) is equal to 0 when the current is maximum or minimum, which results in a temperature increase at the extremities of the vertical sweeping area. It is known that thermal stress on the copper wall leads to a limited lifetime of the collector, due to material fatigue [3], making this technique inappropriate for cw operation of MW-class gyrotrons.

1.2. Transvers Field Sweep System (TFSS)

An alternative sweeping solution, Transverse Field Sweep System, consists of 3 pairs of -coils whose axes are perpendicular to z and spaced equally in azimuthal angle near the lower part of the collector, powered by 3-phase AC-supply generating a transverse field, which rotates at 50Hz [4]. The advantage of sweeping at a higher frequency is to reduce the cyclic thermo-mechanical stress in the collector wall. But again, the sinusoidal variation of the magnetic field leads to a non-uniformity of the power deposition, and the issue of the temperature increase at the collector extremities is not solved. Another weakness of this technique is that, unlike the VFSS, the TFSS cannot generate a static magnetic field in z axis, and thus still requires the presence of a VF coil.

The combination of VFSS and TFSS gives good results to flatten the thermal peaks, allowing adjustment of the strike points along z, at the cost of a voluminous equipment installed around the gyrotron collector that reduces the space for other auxiliaries.

1.3. Amplitude Modulation Sweeping System (AMSS)

Mixing two different sinusoidal waveforms, doing amplitude modulation (AM) on a single system, can have a similar effect as adding VFSS + TFSS. The higher frequency spreads as quickly as possible the electron beam while the lower frequency distributes the power spikes.

All gyrotrons used at SPC are equipped with vertical coils allowing the test of the AM method on VFSS topology. However, the attenuation of the magnetic field inside the collector at high frequency is a hard limitation that needs to be properly addressed.

2. Analysis of the magnetic field attenuation

To find the bandwidth of this system, analysis by the finite element method has been done with Ansys-Maxwell. In this way, it is possible to evaluate the attenuation of the magnetic field at the inner surface of the gyrotron collector for different frequencies, considering all the currents induced. To simplify the model, only the copper part of the collector and the sweeping coil have been integrated in the simulation model without considering the static field created by the cryogenic magnet. Figure 2 shows the attenuation effect of the magnetic field inside the gyrotron.

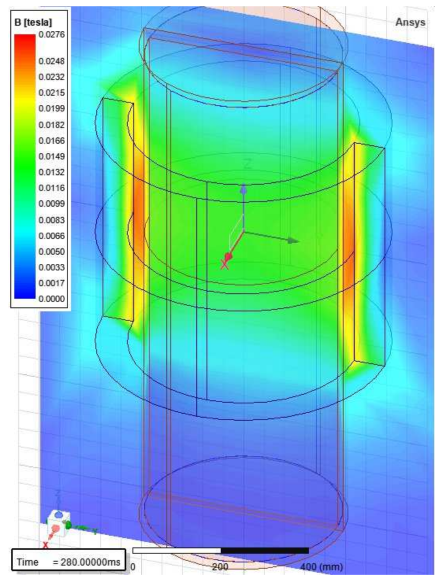

Fig. 2 Magnetic field on the radial Y-Z plan of the collector model.

The simulation was done by generating a frequency sweep of the current in the collector coil made of 1350 turns, with $I_{coil} = 10A$, in the range of 1 to 50Hz. It is represented by the blue line on Figure 3. On the same figure, the orange line represents the magnetic field on the z axis, at the center of the collector, showing clearly the attenuation of B_z when the frequency increases.

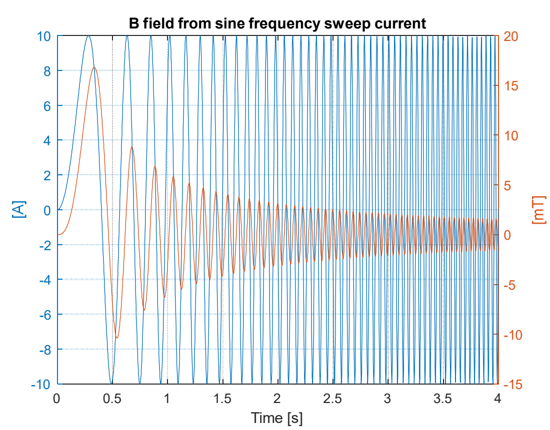

Fig 3. Representation of I_{coil} (blue line) and the result of $B_z(t)$ (orange line) inside the collector

The data extracted from this simulation are plotted in Figure 4 as a Bode diagram. One observes that the collector model behaves as a first order system, so the cut-off frequency is identified by a phase angle of 45°. The frequency bandwidth of the system is therefore $f_{bw} = 2[Hz]$.

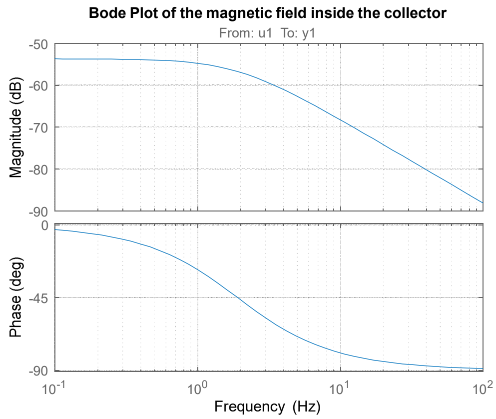

Fig 4. Bode plot of the magnetic field inside the collector

2.1. Choice of the frequencies

Although the bandwidth of the system is known, the choice of the sweeping frequencies is strongly dictated by the physical constraints of the system. The final choice shall take into account different parameters such as:

- the thermal limitation of the collector
- the thermal limitation of the collector coil
- the bandwidth of the power supply, which increases with its size

Based on the gyrotron manufacturer's recommendations, but also tested and approved at SPC over many years of operation on several gyrotrons of the type TH150x, the optimal frequency for VFSS is around 7Hz.

To correctly define the AM signal, it also important to look at its frequency spectrum, in order to ensure that the highest harmonics are not too far from the cut-off frequency of the system, knowing that for an AM signal, the highest harmonic frequency is equal to the sum of the frequency carrier (f_c) and the frequency of the modulation (f_m). Figure 5 shows the AM signal (black) resulting from the frequencies chosen for these tests. With $f_m = 2Hz$ (blue) and $f_c = 7Hz$ (red), and a modulation ratio of 50%, the highest harmonic frequency is 9Hz, i.e. less than a decade away from the cut-off frequency.

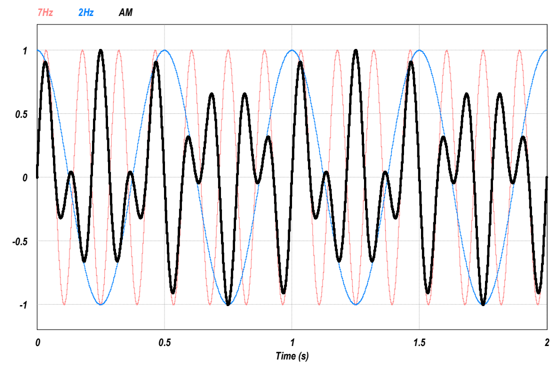

Fig. 5 Amplitude Modulation reference signal

3. Tests and measurements

As a member of the European Gyrotron Consortium (EGYC), SPC has participated in the development of the EU gyrotron for ITER (170GHz/1MW/CW) [5][6]. In parallel, the Tokamak à Configuration Variable (TCV) [7] ECRH system has been recently upgraded with the addition of two MW-class dual-frequency gyrotrons (TH1510, 84 or 126GHz/2s/1MW) procured from TED (Thales Electron Device) [8]. The design of these gyrotrons is based on the commercial TH1507 (140GHz/1MW/CW) built for W7-X [9]. The following tests have been applied on both gyrotron types, using different control systems.

3.1. Hardware

The power supply generating the AM current is the key component of the system. A commercial off-the-shelf power supply EPS/ACS 3000 (figure 6), used on our gyrotrons sweeping system at SPC, is able to follow an external arbitrary waveform reference and to generate the appropriate current and voltage up to 20Apeak/425Vpeak/150Hz, which is by far sufficient for the collector coil. This power supply is acting as a current amplifier, controlled by an external voltage reference. The control system used for the TH1510 is based on a Compact RIO (cRIO) from National Instrument.

Fig. 6 AC+DC power supply - EPS/ACS 3000, 19''/6U

As a reminder, a static magnetic field, or a too slow variation of the latter, could dramatically increase the temperature of the gyrotron collector. Thus, the gyrotron manufacturer insists that the electron beam must not continuously strike the same location for more than 100ms.

To avoid any misuses of the sweeping system, the specific reference waveform integrating the AM is stored in a Look-Up Table (LUT) inside the FPGA of a cRIO and cannot be changed without recompiling. In the same time, the current in the collector coil is measured by an external current transducer (LEM LF-210-S/SP3) and verified by the controller. The logic, based on a dynamic window comparator implemented in a FPGA, will trip the system and stop the gyrotron operation if the current deviates more than 5% from the reference. The bloc scheme of the control system illustrated in figure 7, shows how the controller interacts with the power supply and insures the protection of the system by measuring the current in the coil and the temperatures along the collector.

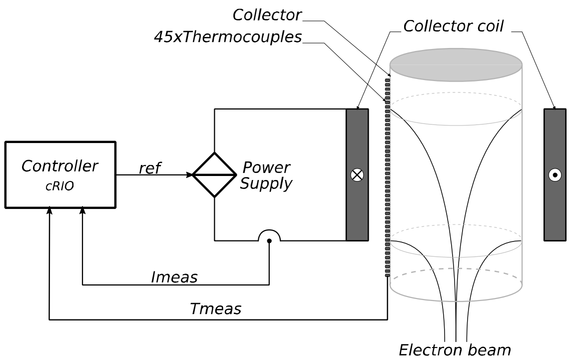

Fig. 7 Bloc scheme of the system

In parallel, this compact controller (figure 8) is also able to proceed with calorimetry measurements on every cooling circuits of the gyrotron [10], as well as measuring the 45 thermocouples placed along the collector in the Z axis (#45 at the top). Displaying these measurements in real-time during the gyrotron operation is particularly useful during the gyrotron commissioning, and allows detecting any degradation of the system during long-term operation.

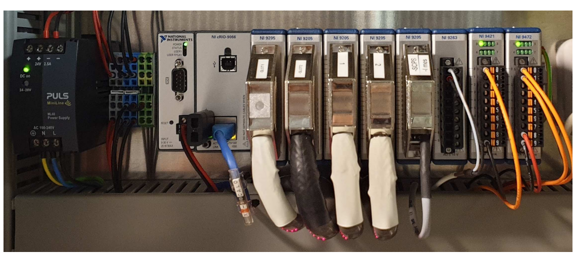

Fig. 8 CompactRIO controller on the dual-frequency gyrotron system

3.2. Tests with two gyrotrons of 1MW

The AMSS solution have been tested on both gyrotron test benches operated at SPC (TCV and Falcon), performing a comparison between VFSS versus AMSS. The European Gyrotron TH1509 for ITER (170GHz/1MW/CW) with depressed collector is shown on figure 9 (tested at Falcon), while the dual-frequency gyrotron TH1510 installed at TCV (84 or 126GHz/1MW/2s) is shown on figure 10.

Fig. 9 EU gyrotron TH1509

Fig. 10 Dual-frequency gyrotron TH1510

Falcon has been used by F4E as a test bench for the control system to be deployed at ITER. The power supply for the vertical sweeping is controlled in voltage with closed-loop regulation. As already anticipated, good performance is obtained with the combination of VFSS and TFSS for cw operation of MW-class gyrotron. So, the TH1509 is equipped with these two systems. For testing the AMSS, the TFSS was, of course, disactivated.

Figures 11 and 12 show the temperatures profiles along the collector, measured by thermocouples inserted on the external side of the collector, when either VFSS or AMSS is applied. Only the maxima recorded during the gyrotron pulse are represented. The comparison of both techniques shows a real advantage in terms of homogeneity when AMSS is applied. The peaks at the extremities are considerably reduced and the elevation temperature is more uniform.

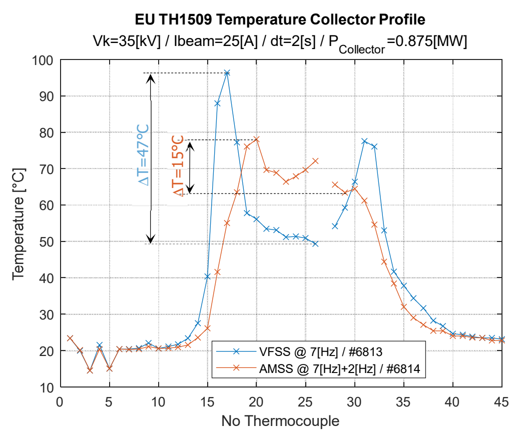

Fig. 11 VFSS vs AMSS on TH1509

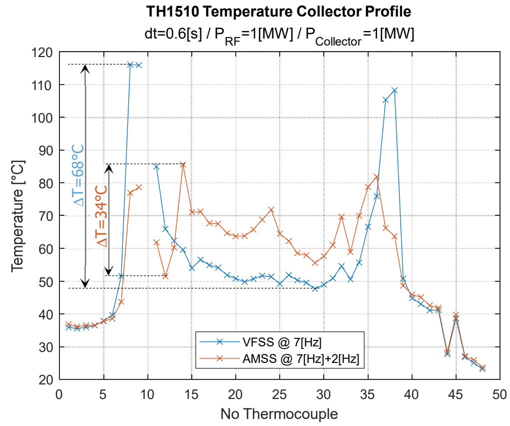

Fig. 12 VFSS vs AMSS on TH1510

4. Conclusion

The thermal peaks along the collector wall are drastically reduced when AMSS is applied, compared to VFSS, making this solution very interesting for existing short pulse gyrotrons, already equipped with a vertical coil collector. Commercial off-the shelf power supplies are available to implement this technique at a minimal cost.

As presently implemented, the collector is acting as a low-pass filter respectively to the magnetic field generated by the collector coil. This low frequency bandwidth does not permit sweeping higher than 10 to 15Hz. In terms of thermo-mechanical stress, it is a limitation for cw operation of MW-class gyrotron, and thus the combination of TFSS+VFSS systems may still perform better than AMSS. The price to pay for that combination is the size of the two systems and their complex installation around the gyrotron tower. Alternatively, a collector made of GlidCop would avoid thermo-mechanical stress, and making the AMSS technique suitable for cw operation of MW-class gyrotron.

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