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Reverberation Chambers at the Edge of Chaos: Discussion Forum at EMC Europe 2020

R. Serra, G. Gradoni, G. Andrieu, V. Mariani Primiani, M. Magdowski, O. Legrand, M. Ahmed

Abstract—Reverberation chambers (RCs) have served yet another purpose, though, this time, a not-so-technical one. At EMC Europe 2020 in Roma, Italy, an open debate has been carried out on some disputing arguments regarding RCs. This debate focused on a (apparent?) confrontation between the “traditional” RCs and the “chaotic” RCs. The fruitful debate inspired, in a novel way, intriguing and captivating comments on the nature, the uses and applications of RCs. The reader will find that there are several topics on which the debaters still disagree. Most probably, the reader him/herself would have a divergent opinion on some of the topics detailed in this paper. These divergences should not represent any major issue but, on the contrary, they should make research even more interesting by acknowledging and reflecting on the exciting complexity of the learning process. This is a rather unusual paper which briefly reports on the main topics and arguments covered during the debate. Furthermore, and perhaps more interestingly, it also reflects on the importance of scientific debates, conversations and exchange of ideas which were experienced during such discussion forum.

I. INTRODUCTION

It has been estimated that by the year 2023, reverberation chambers (RCs) [1], [2], [3] will be the preferred measurement environment for radiated electromagnetic compatibility (EMC) applications [4]. Reverberation chambers have been indeed experiencing a steady growth towards an increasing number of application domains, not only in EMC but including as well over-the-air measurements for antenna and wireless communication systems [5], among others.

Parallel to this trend of an increased number of new applications, RCs’ theory and understanding are constantly being developed as well. Early and widely-adopted theoretical models like [6], [7] constitute some of the basic yet very powerful ways to describe and understand the field dynamics inside RCs. However, these models are not the only ones present in literature for RCs. Several alternative efforts are also available and came about mainly by the fact that models like [6], [7] rely on a series of significantly strong assumptions, such as, for instance the basic assumption that the chamber has to work in the *overmoded* regime (i.e. at significantly short wavelengths, much shorter than the chamber’s size). Further assumptions are that the modes should be “well-stirred”, that the field is considered far from electromagnetically relevant boundaries, that the loading is low or moderate, etc. One particular example of such an alternative model is, for instance, the radiant thermodynamic black body model.

A. Disputations in RC: the antecedent of mode-tuned cavities “vs.” thermodynamics.

The thermodynamic approach applied to the study of the statistical behavior of fields inside RCs is present in a pioneer work by P. Corona and G. Latmiral of 1976 [8] written in Italian. Later, in 2002, a translation to English was published in [9]. The 2002 version has an extraordinary added element, however: it includes several comments from J. Ladbury. The paper contains a written confrontation between two different positions (mode-tuned cavities approach and the thermodynamic approach) on the matter of RCs. Several points of disagreement are relatively minor like, for instance if the term *reverberating* is more suitable than the term *reverberation*. Others are of a more important nature. As an example, the thermodynamics approach, which assumes that the RC resembles a radiant back body, concludes that a cubic-shaped RC will outperform a rectangular cavity, in terms of field homogeneity and field isotropy [10]. While the mode-tuned cavity approach, would predict the opposite, i.e. that cubic-shaped cavities will show a lower performance in terms of field uniformity criteria.

Both the thermodynamic approach and the mode-tuned cavities approach were (still are?) somehow in competition but fruitful scientific exchange has made them “...reciprocally consistent...” (in Corona’s own words) [11].

B. And now... chaos!

A comparable dispute has arisen, relatively recently, with some studies introducing the so-called “chaotic reverberation chambers”. Oftentimes, these chambers have shapes which are inspired in chaotic cavities, but they also include a stirrer in addition (or any other sort of stirring mechanism).

The concept of chaos in the context of RCs is not entirely new. Some initial efforts to describe the field dynamics in terms of classical deterministic chaos can be found in [12]. A very simple 2-D, ray-optical approach is studied in [12], where it is shown how the space-time field homogenization process can be described in terms of Lyapunov exponents (a classical indicator of chaos). In 2004, N. Pasquino proposed a RC whose geometry was inspired in the so-called “chaotic billiards” [13]. Simulations showed that the enclosure exhibits an overall good statistical behavior. The RC, however, was never built and the whole study reduced to the simulations performed in [13].

These previous studies have never raised any major disputes. However, the relatively most recent works which claim to have

physically realized chaotic reverberation chambers have experienced some opposition. Very often, these studies claim that chaotic reverberation chambers can outperform the traditional ones. And this has come, as mentioned in the abstract of this paper, not without controversy.

One key aspect of the dispute is related to a lack of generalized consensus, within the EMC community at least, on the definition of chaotic RCs. While the concept of chaotic cavities, however, is clearly defined in the field of quantum or wave chaos, the concept of chaotic reverberation chambers, in the field of EMC, is not clearly defined for everyone. Therefore, while there is a generally understood and shared view on what chaotic *cavities* are, in one field, it is not yet fully generally accepted what chaotic *reverberation chambers* are, in another field of study.

However, the reader will discover that, thanks to the discussions and exchanges which occurred during EMC Europe 2020 and are reported in this paper, a definition of chaotic reverberation chambers have been distilled from this debate. Chaotic reverberation chambers are not defined by having a specific shape or particular features (although they actually count on some of these aspects). Chaotic RCs seem to be those RCs exhibiting field distributions with statistical properties which can exclusively be predicted by one particular model. This model is known as Random Matrix Theory.

II. CHAOTIC REVERBERATION BILLIARDS?

In order to have an intuitive introduction to the nature of the discussion, let us briefly and simply describe some of the basic points of the different models. The reader must be warned, though, that this introduction should not be considered formal and exhaustive. It only serves the purpose of broad dissemination, in order to give a better context for the debate in this paper.

Let us consider, as an analogy, a two-dimensional box containing two point particles. The particles move at the same constant velocity and reflect specularly at the walls of the box. The starting position of the two particles is slightly different.

Fig. 1 shows the trajectories of these two particles. As can be seen, the trajectories remain very similar to one another keeping, at all times in the evolution of this billiard, a constant distance between them. In our analogy, these particles represent rays coming from a source. The trajectories represent the traces of these rays and therefore they interfere with each other in the whole space of the 2D box, creating a specific wave pattern. This wave trajectory pattern shows a strong regularity and symmetry.

The billiard in Fig. 1 might be a good analogy of an electromagnetic cavity, but it is definitely not a good analogy of a reverberation chamber, for an RC needs a *stirring mechanism* [14]. We can get a good intuition of the role of a stirring mechanism by considering a large object inside the box. Figure 2 shows the trajectories of the same box as in Fig. 1 but with a large scatterer inside the cavity. For simplicity, this scatterer is a circle placed in the center of the box. In practical applications, such circle would be a very poor stirrer, but let

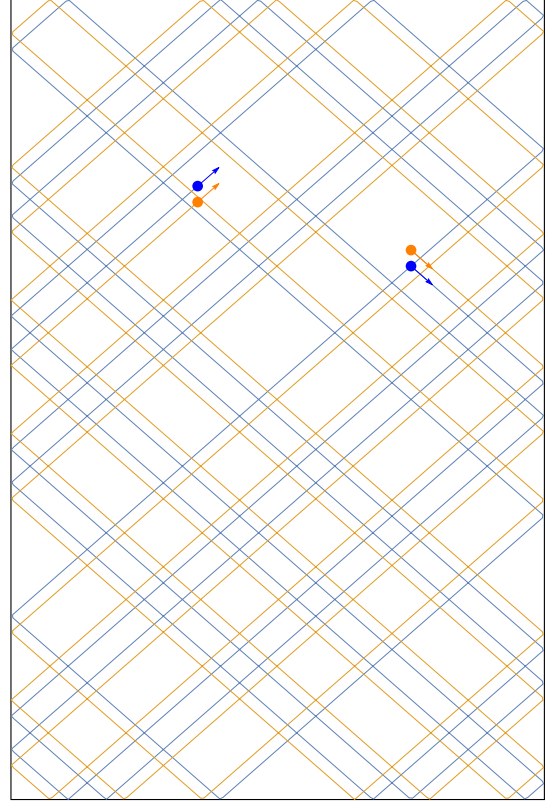


Fig. 1. Point particles moving at the same constant velocity inside a 2D box. The two particles start at slightly different locations inside the box and keep a constant distance between them at any time.

us accept the circular “stirrer” for the sake of simplicity. It can be observed that in the presence of such scatterer, the trajectories of the particles are significantly different from one another. One can easily picture that the interference pattern resulting from a box like the one in Fig. 2 will not show the same regularity and symmetry as the one in Fig. 1.

This way of looking at wave cavities, like the ones in Figs. 1 and 2, is not very common in EMC studies. However, in many branches of physics like acoustics or optics, for instance, the study of wave cavities by describing the trajectories of (ballistic) point particles and their traces is widely used and known as *dynamical billiards*. These billiards are mathematical tools which can basically help to obtain expressions of the modal density in a cavity. By understanding how and how many of these trajectories are periodic, one can describe some useful electromagnetic characteristics of an enclosure by linking its shape to the field dynamics directly, without the need to perform plane-wave decompositions, or computationally-expensive numerical simulations. In cases where the trajectories show an apparent random behaviour, these billiards are then sub-classified as *chaotic billiards* (more precisely they should exhibit what is known as “strong sensitivity to initial conditions”). A classical example of such chaotic billiard is shown in Fig. 3.

Note how the irregularity in the trajectories in Fig. 3 is

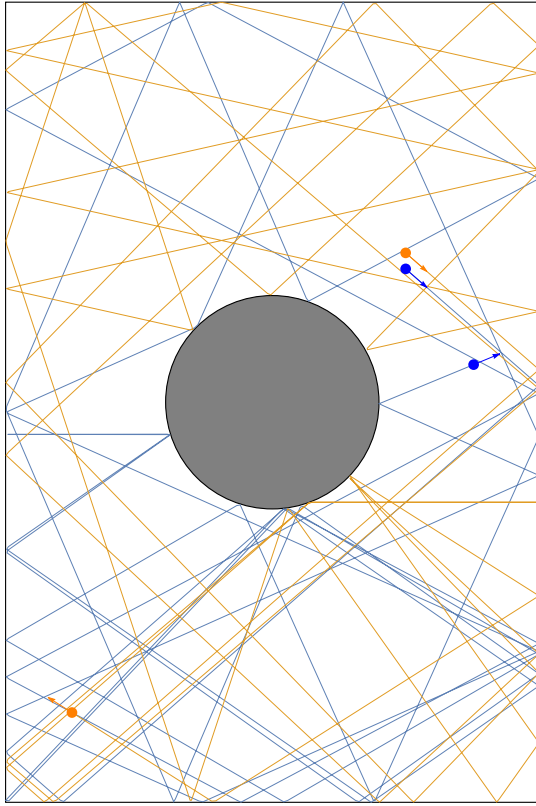


Fig. 2. Point particles moving at the same constant velocity inside a 2D box which includes a large circular scatterer inside. Even though the two particles start at slightly different locations, their trajectories evolve very dissimilar to one another. The traces exhibit an irregular pattern illustrating strong sensitivity to initial conditions.

solely induced by the shape of the walls of this cavity and not by the presence of a scatterer inside it. Several questions then arise naturally like, for instance: could a RC improve its performance (which might already be good enough) if, in addition to including a stirrer, the shape of the walls are made in such a way to favour more irregular trajectories of ray-paths? how different (or not) are the properties of the field dynamics between a situation like Fig. 2 and Fig. 3? Could a practical reverberation chamber, one which includes some sort of mode stirring strategy, be conceived based on the insight from dynamical billiards? And if so, would this chamber bear any significant performance advantage with respect to a chamber whose design is not based on chaotic billiards? Consider, as an example, the graphical visualization of a “chaotic reverberation chamber” in this context, as depicted in Fig. 4. A large scatterer is present inside a chaotic billiard. Therefore, the irregularity of the trajectories is due to a *combination* of effects: the scatterer and the walls. Are these two aspects additive or redundant?

A. Different theories, different insights (and different limitations...)

The different theories and/or models for reverberation chambers aim at making predictions. Each one of these models

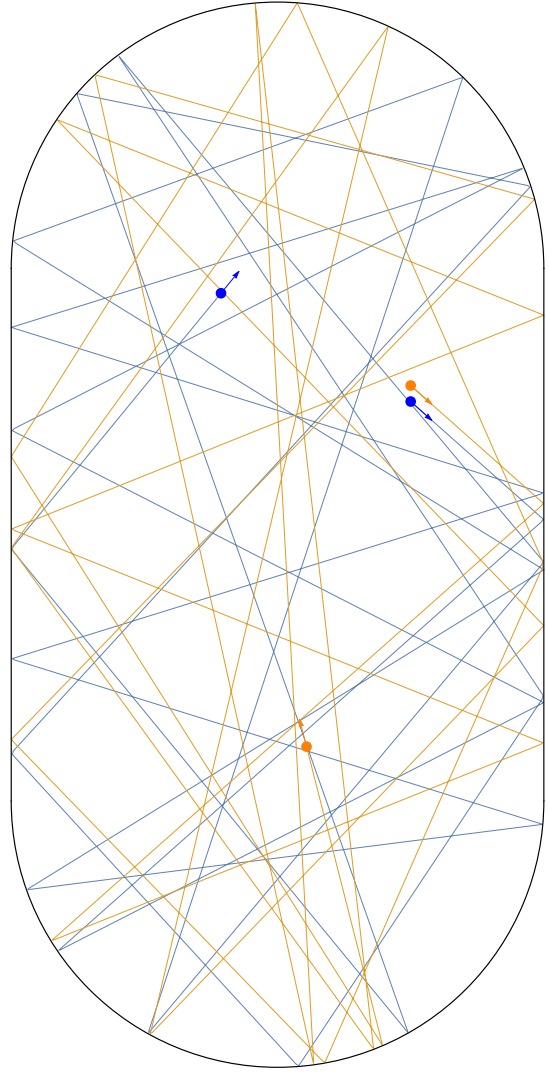


Fig. 3. Point particles moving at the same constant velocity inside a 2D billiard. Even though the two particles start at slightly different locations, their trajectories evolve very dissimilar to one another even in the absence of any large scatterer inside it. The traces exhibit also an irregular pattern.

are based on a certain number of assumptions and rely on them for their applicability. But more importantly, perhaps, is the insight each one of these models can provide. From a thermodynamic black body radiator model [8], to a plane wave integral representation model [7], from a (random) modal expansion [6] to chaotic billiards [15]. All these models try to make suitable predictions in the most simple, universal, practical and applicable way possible.

The model in [7] assumes that the random field inside a RC can be thought of as a superposition of infinite uniform plane waves with random amplitudes, arriving at random angles and phase. This model is clearly asymptotic and therefore only applicable at sufficiently high frequencies. Moreover, this model is hardly applicable when the field is close to boundaries. However its simplicity and high power has turned it into one of the basic models to predict the field dynamics

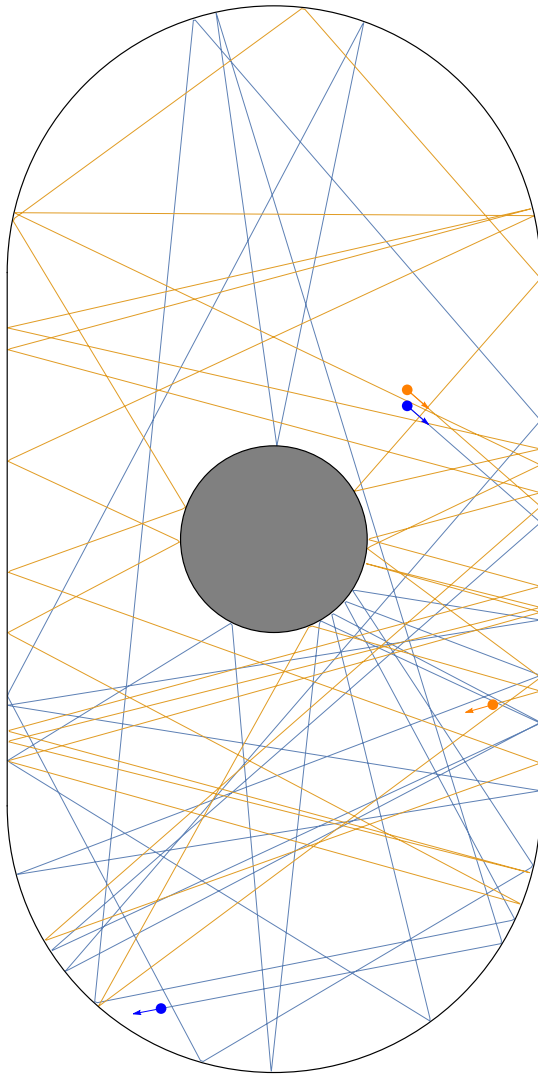


Fig. 4. Point particles moving at the same constant velocity inside a 2D billiard. This chaotic billiard features a large scatterer inside. Could this configuration represent an improved concept for a reverberation chamber?

inside a RC. For instance, in the prediction of the response of an antenna inside a RC.

The model in [6] assumes that the field can be expanded into a series of random resonances. These random modal expansion is also an asymptotic one and requires that the modes behave as independent and identically distributed random variables. None of the contributing modes should be dominating the expansion.

Chaotic RCs are modeled mainly by means of the random matrix theory (RMT). A random matrix is simply a random variable which is matrix-valued. Similar to a random vector, where its individual components are random variables, a random matrix is a matrix whose elements are random variables. RMT was firstly applied in nuclear physics and used to model some aspects of heavy nuclei. Inherently, heavy nuclei lead to large interaction matrices with apparently random elements. Therefore, matrices were the most natural and easy mathe-

matical tool for describing them since the total energy (or Hamiltonian) in quantum mechanics can be naturally modeled as a matrix. In particular, an Hermitian matrix. Later on, RMT has found a myriad of applications in different areas of physics, engineering (and beyond), such as acoustics, control systems, neuroscience and some particular class of electromagnetic cavities. When applied to electromagnetic cavities which exhibit a (quasi-)random behavior, such as reverberation chambers, the most appropriate elements of random matrices are found to be Gaussian random variables. Moreover, for wave systems with time reversal symmetry, the appropriate statistical ensemble is that of symmetric real matrices (like Hermitian matrices), which is known as Gaussian Orthogonal Ensemble (GOE). GOEs can successfully and parsimoniously predict a wide variety of probability distributions for the quantities of interest (for instance, electric field strength, or electric field intensity). Furthermore, it is found that the eigenvalues of such GOE matrices can be made to correspond with the natural responses of a cavity, having a direct link to observable and quantifiable properties of the cavity under consideration.

B. Traditional RCs and chaotic RCs

Traditional and chaotic reverberation chambers share many common features between them and have largely the same uses and applications. They both consist of a metallic enclosure which, when properly excited with antennas inside its volume, can sustain electromagnetic resonances. These resonances are in practice generally driven at relatively high frequencies, to reach the so-called *overmoded* regime, i.e. many resonant modes densely excited. In addition to achieving high modal densities, some type of stirring mechanism must take place, in order to “stir the modes”. Several stirring mechanisms exist [14], arguably, the introduction of a large rotating paddle inside the chamber being the most common one.

As said, both traditional RCs and chaotic RCs share all these same features. What is the difference, then, between a traditional RC and a chaotic RC, in essence? If there are differences, does any of them have a performance advantage over the other one?

C. Why debating on RCs?

Following a recent appearance of the term ‘chaotic RCs’, the electromagnetic compatibility (EMC) community interested in RCs and in chambers and cells in general, has been engaged in conversations and disputations regarding the novelty, the pertinence, the applicability and the usefulness of the models inspired in chaotic cavities. Questions such as:

Can curved diffusers induce chaos in a closed cavity?

Does this chaos yield better performance of a reverberation chamber?

Which models can provide more universal descriptions of the field dynamics in RCs? Field expansions on random eigenmodes [6], random plane wave spectrums [7] like normally accepted in traditional RCs, or non-Hermitian effective Hamiltonians [16] like in microwave experiments?

The list of similar questions is much longer. However, most of these discussions only occur during very brief and limited moments, like, for instance: the five-minute Q&A session after presentations in a conference, during coffee- or lunch-breaks, etc. Therefore, we identified a need and interest in having an open and significant discussion on the topic of (chaotic) reverberation chambers. These discussions would not follow the traditional setup of a workshop or tutorial, i.e. with a series of presentations with limited opposition. On the contrary, they were meant and designed to favor debate, with contrasting positions on crucial questions in the area of chaotic vs. traditional RCs.

Furthermore, in this series of dialectics we aimed at sharing and confronting valuable clarifications, explanations and definitions which will help the RC community (and beyond) as a whole.

D. Why debating, at all?

The aim of the discussion forum was also to introduce and recover the, probably forgotten, healthy exercise of debating, which is an old and significantly valuable habit of University education and scientific conversation. In Fig. 5, an excerpt of the fresco *School of Athens* can be observed. The famous fresco shows an important number of mathematicians, philosophers, thinkers and scientists of ancient Greece. Many of them are engaged in conversations, in sharing their ideas and in learning from each other. The center of the scene is dominated by Aristotle and Plato. Aristotle's right hand indicates the ground. Aristotle argues that if one wants to understand Nature, one needs to make observations and conduct experiments which can be perceived and understood through the senses. Only experiments can tell us the truth behind natural phenomena. Plato disagrees, with his hand pointing upwards. Experiments are biased and corrupted. Senses can be deceitful and can induce us to wrong conclusions. The truth about Nature can only be known by building abstract models. The physical world around us is just an imitation of the world of ideas.

Scientific debates aim at exchanging, in a polite and educated manner, different points of view, while practicing the gymnastics of argumentation, without shouting, offending or being rude. The goal is not to provide a final and definitive solution to these "disputed questions" in such a short session, but to facilitate the healthy exchange of ideas and opinions.

This paper should, therefore, be read not only as a technical report on the topics under discussion, but moreover as a motivated opportunity to expose an efficient and concrete way to trigger adversarial collaborations in research and academic practice.

III. FORMAT

The debate was organized in two parts. Each part dealt with a different question, within the main discussion on chaotic and traditional RCs.

a) *Question 1:* Are (properly designed) curved objects placed inside a RC the responsible for a better RC performance?



Fig. 5. Detail of the fresco known as *School of Athens* by Renaissance artist Raffaello. Plato and Aristotle are engaged in a philosophical debate showing antagonists positions. Plato's hand points the sky, while Aristotle's palm gestures toward the ground. Source: <https://www.museivaticani.va/>

b) *Question 2:* Is there a real distinction between the so-called chaotic chambers and the more traditional reverberation chambers?

Each question had two debaters and a moderator. Each debater assumed one of antagonist positions for either a "yes" or a "no" as answers to the postulated question. The moderator would not ask any questions, would remain totally neutral and his role was solely to organize the debate. Each question was debated in a fixed amount of time (45 minutes approximately) according to the following steps:

- 1) Before the debate begins, members of the audience vote their individual opinions (yes, no, I do not have a formed opinion) and the results are shared immediately.
- 2) Each debater has ten minutes to provide an initial answer to the main question under debate. First, speaker 1 presents his ideas in the allotted time, followed by speaker 2. This first motion to the question under debate is focused on fundamentals and ideas. Each debater shows some evidence/results to back-up his position. This evidence is either the debater's own experience or results extracted from the literature or results shared by colleagues.
- 3) After their initial presentations, each debater has five minutes extra to answer to the first exposition of the opposing speaker and tries to rebut the ideas presented at the beginning. They do so in reverse order from step 2).
- 4) After their presentations and rebuttals, it is time for the audience to ask questions. The audience is invited to either ask a direct question to one of the debaters, or an open question to both of them. The moderator collects the questions which were posed either in the chat-box or by live interventions.
- 5) To finalize, each debater has one final minute to make

a closing remark.

- 6) The audience votes if they have changed their individual opinions after the debate (in either direction).

The first question was debated by Guillaume Andrieu (from XLIM Laboratory, University of Limoges, France) and Valter Mariani Primiani (from Università Politecnica delle Marche, Italy) against and for the motion, respectively. The question was moderated by Ramiro Serra (from Eindhoven University of Technology, the Netherlands). The second question, on the other hand was debated by Mathias Magdowski (from Otto von Guericke University Magdeburg, Germany) and Olivier Legrand (from Université Côte d’Azur, France) against and for the motion, respectively. The question was moderated by Gabriele Gradoni (from University of Nottingham, United Kingdom).

IV. DISCUSSION

This section reports the main points of discussion during the debate, as exposed by the debaters and summarized here for simplicity. The following sections must not be read as a finished piece of scientific publication, but more as a report of what was said and discussed during the debate. Debates are lively and dynamic. We decided to respect the contents and the order of discussion as close as possible to the original ones. We decided not to change what was said. This may give the reader a possible sense of lack of structure or a lack of explanation and context for some of the comments and concepts involved here. To cope with this potential problem, we have added some boxes which can provide some extra context and information. We hope that with this addition, the readability of the debate is increased, while maintaining the fidelity to the exact contents of the debate as it happened.

A. Part I

The first part was moderated by Ramiro Serra, and the question to be debated upon was: *Are (properly designed) curved objects placed inside an RC responsible for better performance?*

1) *First Speaker:* Guillaume Andrieu was the first speaker, making clear that his opinion is “NO”, i.e. curved objects placed inside an RC are not responsible for any significant improvement in the performance of an RC.

He began by acknowledging that RCs with curve geometries diffract rays (in terms of paths) more randomly than those with rectangular shapes, as shown in [17]. Additionally, the appearance of regular modes in curved RCs is also assumed to be less probable compared to rectangular RCs [18].

According to him, however, the presence of the mode stirrer itself, generally designed to have a random geometry avoiding symmetry, already makes the RC modes ‘not perfectly’ regular. Moreover, as schematically represented in red in Fig. 6, the addition of curved objects does not prevent the presence of unstirred paths. Therefore, it seems paradoxical to observe such paths in a facility called ‘chaotic’. He wondered also what would be the minimum size of the curved objects that could guarantee this chaotic behavior.

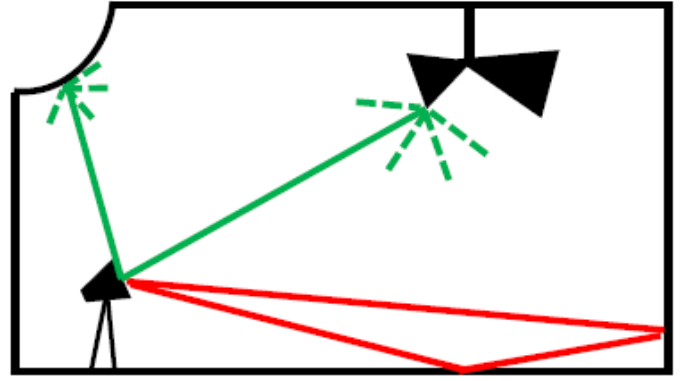


Fig. 6. Schematic illustration of the presence of unstirred paths (shown in red) in a so-called RC chaotic cavity.

Curved objects can favour irregularly distributed modes and so does a traditional, well-performing stirrer.

G. Andrieu also reflected on the words ‘better RC performance’ which appears somehow ambiguous. Do we refer to ‘high mode densities/modal overlap’ at low frequencies? If so, then according to theory, the number of modes (which may be estimated from Weyl’s formula) in a given bandwidth Δf is given by

$$N_m \approx \frac{8\pi}{c^3} \cdot V \cdot f^2 \cdot \Delta f, \quad (1)$$

where V is the volume of the RC, and f is the operating frequency. This means that the modal density depends on the volume of the chamber, and introducing curved objects only leads to a negligible change in the resulting volume of the chamber.

The total volume of the chamber is the leading factor in determining the modal density, not its shape.

Additionally, G. Andrieu identified two sources of ‘potential bias’. When introducing curved objects in an RC, two properties of the resulting chamber are modified: the quality (Q-) factor and the volume. To highlight this, he gave an example of research work conducted at the XLIM Laboratory where irregular objects (two metallic spheres of radius 14 cm, five hemispheres of radius 14 cm, and 20 corrugated aluminium sheets of dimension 1 m \times 27 cm) were inserted into the RC [19]. Ten loading conditions, from 1 to 15 pyramidal absorbers, were considered. This research used the well-stirred condition method [20] as the main performance indicator.

These results (i.e. the frequency at which the RC is well-stirred according to the method) show that the results look different for the parallelepipedic and the chaotic for the same loading condition. For instance, the results are better for the chaotic cavity if no absorbers were inserted in the RC but the inverse result is obtained after the introduction of pyramidal absorbers. The assessment of the Q-factor of the facility (“chaotic” or not) for each loading condition explains these

surprising results. It was indeed shown that there is a slight difference of the Q-factor between the so-called “chaotic” chamber and the traditional RC for the same loading condition in reason of the metallic losses added by the diffracting objects inside the RC. After correcting the effects of the metallic losses by plotting the frequency at which the RC is well-stirred against average mode bandwidth (i.e. $f/Q(f)$), the experiment showed no significant difference between the traditional RC and the “chaotic” chamber. He therefore concluded his first round of speech by advocating that the effect of curved diffractors is null if the objective is to decrease the frequency when a RC is well-stirred (over several stirring conditions).

The modification of the Q-factor of a RC related to the introduction of curved objects, even if slight, could lead to erroneous conclusions on their benefits when comparing a classical RC with its chaotic version.

2) *Second Speaker:* Valter Mariani Primiani spoke in favour of the motion (and therefore advocated for “YES”). According to him, RCs with irregular geometries, such as those with *tilted walls*, *moving walls* and *vibrating walls*, have been shown to exhibit better performance than RCs with regular geometries. For example, there is an observable enhancement of the modal density when spherical diffractors were introduced inside the RC in [21]. Also, a numerical simulation of a traditional RC (TRC) with and without hemispheres (using the CST eigenmode solver) [22], shows a clear distinction between the TRC and the chaotic RC (CRC). In particular, the first 400 eigenmodes of the TRC and the CRC containing 2 hemispheres of radius $r = 150$ mm were compared [22]. Including the hemispheres shows an enhancement of the modal density and modal distribution for both traditional mechanical stirring (rotating paddle) and source stirring achieved by switching several antennas mounted on the chamber walls.

Valter Mariani Primiani added the computation of the number of uncorrelated stirrer positions is usually adopted to check the goodness of an RC and/or of a stirring system, sometimes called “independent stirrer positions”, as in IEC 61000-4-21. The higher this number is, the lower the angle variation needed to create an appreciably different field pattern inside the RC, according to a certain threshold. Typically, by increasing the frequency of operation, this number increases, because the stirrer becomes larger in terms of the wavelength. Nevertheless, in regularly shaped RCs, there are single frequencies where this important number strongly reduces, due to a not sufficiently uniform modal frequency distribution inside the chamber. In [23], for traditional mechanical stirring, it was shown that the introduction of curved objects (spheres each of radius 0.5 m) can significantly reduce (or eliminate) these anomalous frequencies where the uncorrelation drops. Moreover, moving to the frequency stirring method, it has been shown that the introduction of spheres of radius 0.75 m was able to increase the number of uncorrelated frequency steps within a given band [24]. Similar to the ‘number of

uncorrelated samples’, the higher the number of uncorrelated frequencies is, the lower the frequency variation of the input signal required to create an appreciably different field pattern inside the chamber. Also in the multiple monopole source stirring, the number of frequencies for which the hypothesis for chaos is rejected reduces by adding spheres inside the RC [22].

In his final argument, Valter Mariani Primiani shows that the introduction of spherical diffractors improves the field uniformity to conform to IEC 61000 – 4 – 21 standard [25].

When properly designed curved objects are placed inside a RC, several simulation and measurement studies show an improved modal density, an increased number of uncorrelated configurations (either by the stirrer or by changing the frequency) and a lower number of anomalies in the total number of uncorrelated samples. Field uniformity is also improved.

In conclusion, Valter Mariani Primiani emphasised the importance of the modifier “*properly designed*” in the question under debate. Design in terms of shape, dimension, number, and position of the diffractors is essential. Of course, introducing the diffractors reduces the volume of the RC and consequently the availability of the working volume. There is the need for a compromise between the number of diffractors and the working volume available.

3) *Rebuttals:* Valter Mariani Primiani began the rebuttal by saying that it is not only the number of modes that is important but also the frequency distribution of modes. So emphasising the number of modes in Guillaume Andrieu’s argument only tells half of the story. Including the spherical diffractors leads to a more uniform mode distribution as was shown before. Finally, the reduction of the quality factor due to the introduction of spherical diffractors is true in principle. However, in some results obtained (which was not shown because of time), they have shown that the average maximum-to-mean ratio of the received power remains the same with and without the diffractors. The reduction in the quality factor is therefore not significant. All in all, the introduction of spheres improves the performance of RCs.

He was quick to add that most of the studies comparing the performance of CRCs and TRCs use an empty reverberation chamber. When equipment and devices are included within the chamber, the results may be different. He encouraged further research on the comparison between the performance of TRCs and CRCs in the presence of an equipment under test (EUT). This should be carried out from both academics and industrial players.

Valter Mariani Primiani also remarks the importance of assessing that RC chaoticity persists when an EUT is inserted in the working volume. In such study, EUTs of different dimensions should be considered as they constitute different loads for the chamber - thus changing the internal losses more or less significantly.

Guillaume Andrieu began his rebuttal by reiterating that most experimental results include stirrers that are larger than the spherical objects. Therefore, the influence of the moving stirrer on the RC performance would logically overshadow the contributions of the motionless curved diffractors. He asked to the audience that if the volume before and after adding spherical diffractors remain approximately the same, what are the physics-based reasons behind the so-called improvement? He still believes that the impact on the number, distribution and shape of the modified modes due to the introduction of curved objects is insignificant.

Furthermore, in the results shown by Valter Mariani Primiani, the change in the Q-factor from the addition of the curved diffractors is not taken into account (because this information is not available to the researcher). Even if the Q-factor modification is slight, this has a direct influence on the RC behavior. G. Andrieu explains that adding absorbers increases the correlation but improves the field distribution [26]. This, he said, can be found in numerous papers. If the introduction of small objects modifies so deeply the characteristics of RCs, we cannot neglect the effects of such introduction on the Q-factor. Finally, he threw an open question to all attendees. His question goes like this “If I have a well-stirred chamber at 500 MHz, what do we expect from that chamber when we introduce curved objects? Is it that we want to prove that it is well-stirred at say 490 MHz? or are we looking at a revolutionary improvement at say 350 MHz or 400 MHz? What does ‘improvement’ in this regard mean?”.

4) *Questions and contributions from the audience:* Alfredo De Leo (from Università Politecnica delle Marche, Italy) started by making a contribution and supporting Valter Mariani Primiani’s arguments about the shape of the scatterers. He added that the shape of the scatterers is very important in order to observe an enhancement in the performance of RCs. He asked the question if there is any research comparing the performance of objects with different shapes (for example a sphere and a cube)? How do we estimate the goodness of the scatterer *a priori* without using the RCs (maybe in free space)? Can we expect a significant improvement between say flat objects and curved objects in free space at microwave or RF frequencies?

Guillaume Andrieu added that “maybe” objects with larger radar cross-section could work better according to his initial thoughts on the question. Mathias Magdowski comments in the chat that extensive work has been done about measuring the chaoticity of objects depending on their shapes [27]–[29]. These includes the scattering by spherical objects [27], the effects of different sizes and shapes of the stirrer [28], [30], the effects of lining the walls of the chamber by pseudo-random phase reflection gratings [29] or diffusers [31], and the use of non-parallel walls with fixed diffusers [32]. All these have been shown to improve the field characteristics of reverberation chambers.

Alfredo De Leo went further to ask what the best parameter used to quantify the “chaoticity” of a chamber would be? Valter Mariani Primiani supported the answer given by

Guillaume Andrieu (that the best performance indicator is the radar cross-section of the objects at high frequency regime). At low frequency the radar cross-section may not be a good indicator in Valter Mariani Primiani’s opinion.

Philippe Besnier (from INSA Rennes, France) made a comment instead of a question. According to him, there are three aspects to look at when comparing the performance of RCs. The first aspect is the theoretical predictions. Theoretically, it has been established that the spacing between consecutive modes of irregular cavities has a unique distribution which is very different from the distribution observed from regular cavities. The second aspect has to do with the experimental validation of these theoretical predictions. There are adequate experimental models from different branches of physics that can validate the theoretical predictions. The third aspect is the knowledge from the EMC world, which deals with stirrers and curved objects which may improve the chaoticity of RCs. Within the EMC world, he has identified two problems that needed to be tackled. The first has to do with the stirrer itself. According to him, the stirrer itself gives some level of “chaoticity” to RCs. It is highly probable that a good stirrer alone may be responsible for making the RC chaotic (or almost chaotic). The second problem that needs to be looked into is what Guillaume Andrieu has alluded to. That is, it is difficult to change one parameter at a time in a chamber, but if you have a sphere you can change the global “chaoticity” in some way. But this cannot be done without changing the modal overlap or the Q-factor and there is indeed the need to assess that the local modal overlapping is improved by the presence of curved objects.

5) *Concluding Remarks from the speakers:* Valter Mariani Primiani concluded by saying that some parameters are improved by the introduction of curved objects which are “properly designed”. These parameters include the uncorrelated frequency steps, the uncorrelated stirrer angles, and the uncorrelated spatial positions. The ratio of the maximum power to average power is maintained or improved at certain frequencies. Finally, he encouraged more experiments to be carried out in the presence real EUTs.

Guillaume Andrieu, on the other hand reacted to Philippe Besnier’s comment earlier concerning existing theories in physics. He highlighted the difference between what the EMC community is interested in and what theoretical physicists predict. According to him, the EMC community is mostly concerned in ensemble averages of the field/power across different stirring conditions (i.e. mode stirrer positions for instance). The argument that the curved object enables to obtain a better uniform mode distribution is true for one particular mode stirrer position but this effect has no influence on the performance of a RC during a classical application.

Ramiro Serra announced the results of polling at the beginning of the debate as 43% for “YES” voters, 43% for “NO” voters and 14% for “I do not have a formed opinion” voters. He then asked the audience for the second vote to find out how the discussion has influenced or shaped the opinions of the attendees. This vote resulted in 23% of the voters stating

that the debate has helped them changed their opinion on the question under debate, against a 77% of voters who have not changed their opinions.

B. Part II

The second part was moderated by Gabriele Gradoni, and the question to be debated upon was: *Is there a real distinction between the so-called chaotic chambers and the more traditional reverberation chambers?*

1) *First Speaker:* Mathias Magdowski spoke against the motion. He briefly introduced reverberation chambers and how he understood the concept of RC “chaoticity”. For radiated measurements, there is the need for a homogeneous and isotropic field within a certain acceptable standard deviation. With regards to chaoticity, he explained the concept by using classical systems, including the double pendulum (stimulated without friction), whose trajectory is chaotic in nature. Such a system is deterministic, non-linear, and highly sensitive to initial conditions so that slight changes result in a significant difference of the trajectory. According to him, the following definition of chaos is ideal for his presentation.

Edward Lorenz’s definition of chaos states that “*Chaos [is observed] when the present determines the future, but the approximate present does not approximately determine the future.*” [33].

Mathias Magdowski gave other examples of classically chaotic systems such as billiard boards, bingo machines, turbulence, and Chua’s electronic circuit. He proceeded to explain the “difference” between traditional reverberation chambers and the so-called “chaotic” chambers, which are often modelled by a very symmetric structure whose symmetry is broken by introducing e. g. spherical diffractors. To buttress his argument, he showed results from selected research works [15], [24], [34]–[37]. In his argument, traditional chambers already contain a lot of complex shaped objects, nonparallel walls, wall joints, shielding doors, antennas, cables, and stirrers which break up the symmetry, so he is not convinced of any difference between TRCs and CRCs.

The natural geometrical asymmetries and the presence of the stirrer provide TRCs with enough *complexity* and *irregularity*.

In his concluding remarks, Mathias Magdowski exposed that since Maxwell’s equations are linear, fixed electromagnetic boundary conditions will always lead to a fixed solution of the field distribution regardless of the complexity of the cavity. Even in the so-called “chaotic” chambers, the field will not stir itself, but rather requires a stirrer in order to obtain the desired field distribution. The contribution of curved objects may not be what makes the chamber chaotic. Finally, the harmonic excitation may or may not lead to the so-called *butterfly effect*, which is a telltale signature of chaos.

The dynamics of the electromagnetic field inside any resonant cavity are not in correspondence with the definition and understanding of classical chaos.

Mathias Magdowski’s final answer to the debated question is “*Probably NO*”. However, he feels that a true chaotic chamber seems to be the vibrating intrinsic reverberation chamber (VIRC).

2) *Second Speaker:* Olivier Legrand began his arguments in favour of the motion by explaining what a chaotic cavity is. As stated by him, the spectral properties (such as the level spacing distribution) of chaotic cavities obey the theoretical predictions deduced from RMT.

Spectral properties generally refer to some properties of square matrices and matrix operators. Eigenvectors and eigenvalues are such properties, for instance. Level spacing refers to the distance between consecutive elements of an ordered set of numbers. In this context, it refers to how the distance between neighbouring resonant frequencies is distributed.

He went further to show the distribution of the spacings between resonance frequencies of a typical chaotic cavity and indicated the appearance of level repulsion as expected from RMT. He mentioned that regular cavities do not exhibit level repulsion.

Level repulsion is a concept from quantum mechanics where natural oscillations of a dynamical system tend to be as separate in value as possible from one another. These natural oscillations will never share the same frequency in chaotic systems, while for non-chaotic ones they could be as close as possible.

Moreover, regarding the spatial statistics of the field in a chaotic cavity, it is common knowledge that each resonant mode follows a Gaussian distribution. Both spectral and spatial statistical properties of chaotic cavities are closely related to the predictions of RMT, corresponding to the Gaussian Orthogonal Ensemble (GOE) when the system is lossless or a modified RMT including coupling for open lossy systems [38] [39] [40] [41]. He then went on further to argue that the key parameter in this discussion is the modal overlap, which is given by

$$d = \frac{\langle \Gamma_n \rangle}{\Delta}, \quad (2)$$

where $\langle \Gamma_n \rangle$ is the mean width of the resonances, and Δ is the mean spacing between their central frequencies. In the low frequency range, the resonances can be resolved individually, corresponding to a regime of *weak modal overlap*. In the high frequency regime, resonance broadening together with high modal density lead to strong modal overlap. The ensuing superposition of a large number of modes leads to Gaussian statistics. This is the main reason why Hill’s hypothesis holds

true in the strong modal overlap regime. However, if one is interested in “well-stirred” and statistically reliable RCs near the *Lowest Usable Frequency* (LUF) where the modal overlap is moderate, then chaotic RCs can do the job in a much better way than the traditional ones.

RMT is intimately linked to the concept of wave chaos in cavities. A cavity can be qualified as chaotic from the wave point of view if the predictions of RMT can be applied at any regime and for any level of modal overlap. Models like the plane-wave integral representation [7] or the random modal expansion [6] can only predict the field dynamics of regular chambers asymptotically. So a chaotic chamber is one which exhibits characteristics from RMT for a broad range of operation conditions.

Olivier Legrand and his group have recently used RCs with walls made up of reconfigurable meta-surfaces whose pixels are tunable to either Dirichlet or Neumann boundary conditions for the field reflections [42]. They turn out to be well-stirred CRCs.

The “real” difference, as he stated, between a TRC and a CRC was clearly exemplified in an experimental result comparing both types of RCs by investigating the field uniformity in both chambers and assessed by the criterion in the IEC 61000 – 4 – 21 standard.

The results from the two different RCs were compared with RMT predictions for a chamber with modal overlap of approximately 0.89 (implying that the measurement was carried out in the weak modal overlap regime) [43]. The results from the TRC clearly deviates from the RMT predictions, while the CRC’s response agrees well with the RMT predictions.

Moreover, he showed that the CRC satisfied the IEC standard while the TRC did not [43]. In his presentation, he showed a field animation which suggested that, at some positions of the stirrer, the regularity of the modes in the TRC was clearly pronounced, thus precluding a reliable statistical analysis.

Olivier Legrand concluded his talk by claiming that “there are real differences” between the so-called chaotic RCs and the more traditional ones. He further reiterated that, in order for a TRC to be described by Hill’s model, the frequency of operation must be well above the LUF. Below or near the LUF, the field statistics in a TRC deviate significantly from Hill’s hypothesis. The traditional stirrers in addition to the regularity of the RC are mainly responsible for these deviations. In CRCs, the RMT predictions (for open systems) works well, and the field statistics are universal, depending only on one parameter, namely the modal overlap.

3) *Rebuttals*: In the rebuttals, Olivier Legrand specified that the concept of chaos in this context is not about the wave equations becoming non-linear. It is rather about complexity of the objects inside the RCs, where you can expect that the predictions of RMT can be applied. He further explained that, with the reconfigurable meta-surfaces on the walls of

the chamber, it is shown that even for flat walls, these meta-surfaces can yield all the statistical features of CRCs.

Furthermore, when an object (neither too absorptive nor too resonant) is inserted into a chaotic chamber, it does not significantly change the chaotic character of the chamber. He concluded his rebuttal by saying that Mathias Magdowski’s argument is based on dynamical systems, but a chamber is not a chaotic dynamical system. Chambers are qualified as chaotic mainly from the fact that both spectral and spatial statistics are robust due to the underlying chaoticity of the ray dynamics (in the case of cavities with spherical diffractors). In cavities with parallel flat surfaces for example, it is possible to have marginally stable orbits (like those in bouncing ball orbits), which lead to deviations from RMT predictions. These orbits must therefore be avoided in order to obtain truly chaotic chambers.

Mathias Magdowski’s rebuttal started by reiterating that, the term “chaotic” is a matter of definition. Is chaoticity of a chamber only related to predictions of random matrix theory with robust statistics? Or is it related to chambers that are well-stirred with good field properties? In most simulations, perfectly symmetric cavities are used, where the symmetry is broken by including irregular objects so that the statistical field properties improve. However, in real practical chambers, the geometry of the chamber is never symmetric. For example, there are wall joints, door handles, cables, antennas, and other objects which already break the symmetry of the chamber even before the inclusion of the curved objects. The normalised deviation (in dB) of a chamber with and without spheres show no significant difference between the two chambers both in the low and high frequency regimes. Also, the field anisotropy of the two chambers shows no real difference. He showed a study that was carefully conducted so that only the effect of the spherical objects is measured (and not the effects of stirring that occurred as a result of antenna movement for example) [44]. In that research no real differences were found between the traditional chamber and the so-called “chaotic” chamber. In the end, he concluded by saying “it is only a matter of definition of what is meant by chaotic chamber”.

4) *Questions and contributions from the audience*: Frank Leferink (from Thales Nederland and University of Twente, the Netherlands) was invited to make a comment, where he stated that the change in boundary conditions is needed in electromagnetic applications while for other applications such as acoustics, the change in boundary conditions is not as important.

The comment aims at separating the discussion about the shape and form of the resonances in a cavity from the way these resonances are stirred. A resonant enclosure is a necessary though not sufficient condition for reverberation.

Olivier Legrand (the speaker in favour of the motion) insisted that in chaotic cavities without mechanical stirrers, one may use the stirring that occurs due to the change of antenna

positions to achieve field distributions that are predictable by RMT. He is convinced that meta-surfaces could be ideal for achieving a truly chaotic chamber. However, both Frank Leferink and Olivier Legrand agreed that moving the antenna changes the boundary conditions and it is therefore another form of mode-stirring.

Ulrich Kuhl (from Université Côte d'Azur, France) put forward his argument based on the quantum chaos perspective. He said that all classically meta-stable states have to be destroyed in order to achieve a fully chaotic cavity. The system with only a stirrer is chaotic in the spirit of classical chaos, but the introduction of the spheres are able to destroy the meta-stable states and therefore will result in a fully chaotic cavity. It is also important to make sure that the deviations introduced by curved diffractors compared to the wavelength are significant. By introducing curved objects inside the chamber, even a single mode shows all the characteristics that are required for a chamber to be classified as chaotic. But with traditional chambers even at high frequencies there is a possibility of observing a meta-stable state that is responsible for the deviations from RMT predictions (especially in the tail of the distributions).

Olivier Legrand waded in by showing another experimental results from Eindhoven University of Technology. In the results, a comparison is made between the probability density functions (of normalised intensity - the square field divided by its mean) of an RMT prediction and the so-called exponential model alongside measurement results. The measurement results were shown to be closer to the RMT model than the exponential model. The measurement was performed in a VIRC where five of the walls were movable. The floor wall is the only stationary wall in the VIRC¹.

The exponential model is the expected distribution for the field intensity according to [7].

Guillaume Andrieu asked a question which was based on whether there exist a direct path (deterministic path) in the case of an RC with curved surface. To this question, Olivier Legrand admits of having that challenge even with the configurable meta-surfaces. Direct paths from early reflection cannot be easily removed because not all the walls were covered with these meta-surfaces. This is the case even in RCs with hemispheres. But it is common practice to subtract the average of stirring from the scattering matrix. The stirred component of the scattering matrix still have statistical features of a chaotic cavity.

To the same question, Mathias Magdowski added that in a very large chamber with a small EUT, where the EUT can be assumed to not drastically change the field distribution, it is fairly possible to analyse the robustness of the field distribution

more accurately. But in a chamber with a large EUT (that heavily loads the chamber), the hemispheres (or the curve objects) will have a negligible influence on the performance of the RC. This will be the case even close to the LUF. Frank Leferink supported Mathias Magdowski's opinion and added that isotropy and "good" uniformity is the ultimate aim in many research work. The challenge is that idealised theoretical models are slightly different from realistic chambers in terms of symmetry.

The last question in this section was asked by Yi Huang (from University of Liverpool, United Kingdom): Since the boundary conditions may be changed by mechanical or electrical methods, etc., he wanted to know under which category the so-called chaotic reverberation chamber falls.

Olivier Legrand answered the question by saying that chaotic chambers may belong to any of the categories mentioned, because either fixed hemispheres together with a stirrer or reconfigurable meta-surfaces can be used. Another way of changing the boundary conditions is through the use of a VIRC. In all cases, chaotic RCs can be obtained if the statistical properties of the field (either spectral or spatial) can be predicted by RMT.

5) *Concluding Remarks from Speakers:* Mathias Magdowski's concluding remarks were centred on the fact that both well-stirred and the so-called chaotic chambers provide suitable environment for a variety of EMC tests. Reverberation chambers replicates the real life scenarios better than the traditional anechoic chambers, especially at high frequencies. Mathias Magdowski's slides can be found on *slideshare* at [45].

Olivier Legrand emphasised that if one can "create" a chamber in any form whose properties can be predicted by RMT, then one can guarantee the robustness of the field statistics, even at low frequencies where there are only few modes. Breaking of symmetry is obviously necessary, but not sufficient for a chamber to be categorised as chaotic.

Ramiro Serra announced the results of polling at the beginning of the debate as 37% for "YES" voters, 54% for "NO" voters and 9% for "I do not have a formed opinion" voters. He then asked the audience for the second vote to find out how the discussion has influenced or shaped the opinions of the attendees. This vote resulted in 16% of the voters stating that the debate has helped them changed their opinion on the question under debate, against an 84% of voters who have not changed their opinions.

V. POLLING RESULTS AND ATTENDANCE

Ramiro Serra shared the final polling results for both the sessions, that are both reported in Fig. 7.

The results of the polling show the discrepancy in opinions over a crucial and important aspect of the understanding, use and optimization of RCs. It also shows the power of being confronted with a healthy exchange of opinions, arguments and ideas, helping the audience to re consider their positions and change their opinions (in any direction). Unlike other types of debates (like political or economic ones) in scientific

¹Ramiro Serra clarifies that those measurements were performed at the University of Twente by Robert Vogt and Frank Leferink. They shared the data with Ramiro Serra to be able to make the analysis. This is not (yet) a publication, only a bachelor final project but Ramiro Serra and a student are working to make this work more solid and submit it for review.

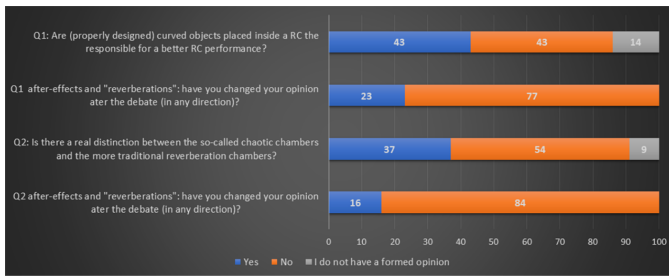


Fig. 7. Polling results the debates.

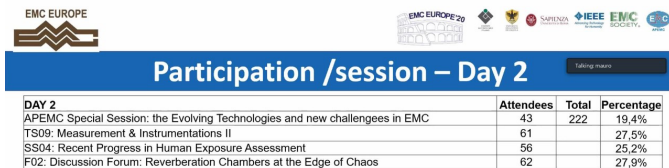


Fig. 8. Ranking of Forum recording online visits.

debates there are not ‘winners’ nor ‘losers’ and the sole gymnastics of scientific conversation is worthwhile the time and effort.

The session live attendance peaked at 62 attendees, making it the highest ranked forum among the four available forums in parallel, in terms of number of attendees. An evidence of this is shown in the statistics of Fig. 8.

To conclude, Gabriele Gradoni thanked all participants for the great contributions and discussion in this all-important debate, and hoped that such discussions continue in the future. On his part, Ramiro Serra also thanked the participants for their time, and made it clear that he has also enjoyed the debate just like any other participant. He urged for more of such debates because debates are natural process of thinking. We can argue on many things but we essentially agree that we are all looking for a better chamber and for a higher penetration of this technology into industrial and academic use. That is the common denominator. He hoped this first debate will not be the last, so that we can continue this conversation.

VI. REFLECTIONS AND REVERBERATIONS

The exercise, apart from contributing to common knowledge by defining, clarifying and confronting ideas and concepts regarding RCs, also left room for some further reflections and ‘takeaways’. On one hand, the urge to count on more frequent and deeper opportunities to exercise proper scientific exchange and, on the other hand, it triggered some reflections on the perceived novelty of a format, i.e. the debate, which is however a long-standing, deep-rooted tradition in academia.

A. Exercise scientific conversation: essential, urgent and (hopefully) emergent.

There is little doubt about the inalienable power that scientific conversation can bring about. Mainly because scientific literature is essentially self-correcting through peer-review,

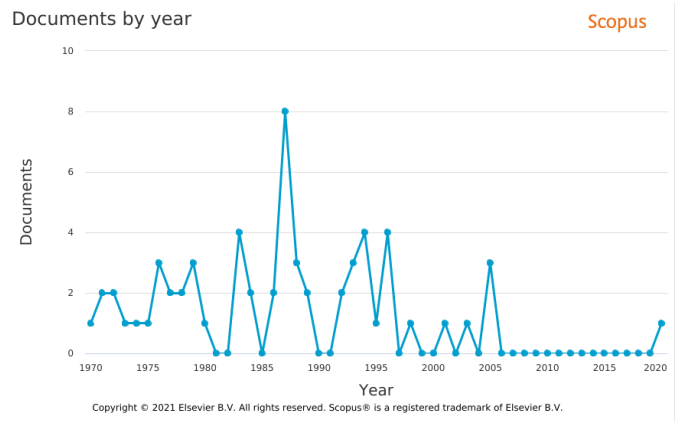


Fig. 9. Number of notes and errata published in the IEEE Transactions on EMC with the keywords *comment* or *comments* in the title. Source: Scopus

comments and errata. Furthermore, by the habits of exchanging ideas, providing opposition and confrontation, arguing and counter-arguing, fostering proper and pertinent definitions, providing clarifications and clear examples and analogies, among other habits, scientific knowledge can progress and evolve faster, more solid and can accelerate towards shared consensus.

Conversation can be either oral or written. Unfortunately, we experience a very low rate of correction and confrontation in our discipline. Figure 9 shows the number of documents with the word “comment” or “comments” in the title published in the IEEE Transactions on EMC per year. Only notes and errata are counted, since these are typically the document types indexed in Scopus for corrigenda²

Hopefully, we can all feel encouraged to become more active to publish or to discuss commentaries, refutations and corrections. This attitude will sustain and ensure a vigorous scientific exchange through debate and collaboration.

B. To innovate is to inveterate

During the final (online) ceremony of the EMC Europe 2020 conference, the “Reverberation chambers at the edge of chaos” session was awarded a “Certificate of appreciation for the most innovative and original Focus Event”. This certificate represents an honor for the organizers and they appreciate the recognition. The award help us also reflect on the fact that a public debate might be perceived as innovative and original but debates have been accompanying and supporting the progress of human knowledge since the (known) origins of organized knowledge. For instance, in the Platonic dialogues, Socrates is constantly arguing and testing his own beliefs as a thinking and discovery *method*. Debates also occupied a crucial role all through the early University education in the scholastic tradition. One prominent example can be found in all the

²The results were obtained with the following search in Scopus and may include a small number of retractions: (comment*) AND (LIMIT-TO (DOCTYPE , "no") OR LIMIT-TO (DOCTYPE , "er")) AND (LIMIT-TO (EXACTSRCTITLE , "IEEE Transactions On Electromagnetic Compatibility")) .

articles of the *Summa Theologica*, where Thomas Aquinas always poses three objections to his own statements before attempting to answer them. Even in more recent times, the Bohr-Einstein debates were a series of public disputes held at the beginning of the twentieth century which helped built the foundation for quantum mechanics.

These few examples (the list is clearly not exhaustive) suggests a strong tradition of dialogue and debate in many different areas of human knowledge. How can, then, such an old habit be considered an innovative and original initiative?

In Raffello's fresco *School of Athens*, partially reproduced in Fig. 5, Plato is holding the *Timaeus*, one of his books. At the beginning of the *Timaeus* there is an interesting story told by Solon, who was an important public figure and poet from Athens. Solon had travelled to Egypt and there he learns about the city of Atlantis, a lost naval power which had attacked Europe and Asia many times in the past. This is revealed to Solon by an old priest, who attributes Solon's ignorance of Atlantis to the periodic natural catastrophes erasing memory and knowledge in Greece. To the old priest, Egypt is exempted of these catastrophes, due to the position they occupied near the Nile, and therefore more able to keep knowledge. 'O Solon, Solon,' says the priest, 'you Hellenes are never anything but children, and there is not an old man among you. (...) in mind you are all young; there is no old opinion handed down among you by ancient tradition, nor any science which is hoary with age.' This is how Plato attempts to explain why the Greeks did not retain any memory about Atlantis: natural catastrophes force them to forget the past, the knowledge gained, and are condemned to start over and over again. Egypt does not have to go through this cycle and so they are better keepers of knowledge which "has aged".

We reflect on the point that maybe some catastrophes (not natural ones like fire or flooding but maybe educational or cultural ones) have made us forget the knowledge which has aged. We lost "grey hair" knowledge which could make us great well. One of the crucial habits which has been lost are debates, which were, in other ages, very common and fruitful.

More than innovating, we were inveterating by recovering back an essential exercise in scientific conversation.

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