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Article

Spin orientation manipulation by electric fields and x-ray irradiation

by Mariia Filianina

Neuroscience of Change

Why your brain is hard-wired to react negatively to changes

Interviews

Prof. Dr. Sebastian Seiffert - Education

Dr. Martina R. Hestericová - Women in Science

Never Change a Winning Team

Perspectives from industry, politics and academia on this topic

NEVER CHANGE A WINNING TEAM?!

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Preface

Editorial Note

"Nature knows no pause in progress and development, and attaches her curse on all inaction."

Johann Wolfgang von Goethe

Dear Reader,

The ongoing pandemic still has a tight grasp on all our lives. This pandemic disrupted our daily lives on almost every level. The disruption created a strong requirement for adaption whether for companies, governments, or the individual. Our lives changed: some had to lay off work, some started to work from home entirely, many people had to adopt manners that were unthinkable just one year ago. Such perils as the pandemic are like a catalyst for development since they require action and punish all inaction immediately. Therefore we take a look at the mindset of rejecting change as long as possible. This principle comes in many forms: "If it ain't broke don't fix it", "Never change a winning team", "Never change a running system". It is a mindset that was also observable throughout the last months. The WHO warned from the danger of an upcoming pandemic and the lack of preparation worldwide, time and time again. So far, we were always lucky. In 2009 with the swine flu it worked out, right? Well, as we know now, not this time. This issue is dedicated to the phenomenon that gives us a false feeling of security. We will explore the source, where all ideas of progress come from, in an essay about the neuroscience of change on page 2. On page 8 we discover and discuss the difficulties of changing something in education together with Sebastian Seiffert. Besides, we talk about the struggle of women trying to advance in science with Martina R. Hestericová on page 11. We created a survey on the matter at hand and distributed it throughout companies, political parties, and academia to feature different perspectives on page 13. Ultimately we hope to not only shed some light on the driving force of rejecting progress whether in climate change or corona measures. We also question the morality of eating Hawaiian pizza and more to brighten your mood in these dark times with our questions of the month. No matter how difficult and long this struggle will be, until we come through we must not forget the things that make our lives worth living, otherwise, we have already lost.

— Kevin Machel

Opinions

Neuroscience of Change

Mariia Filianina

Nature made humans resistant to change. Seemingly surprising, given that we live in an ever-changing world and, in fact, are constantly changing ourselves on a chemical level, this statement can find support in many minds. We do not like change and this is not because we are lazy or full of subconscious fears and prejudice. The reason for this lies in our brain that, in the course of evolution, became hardwired to react negatively to change or rather uncertainty so intimately associated with it.

In fact, accordion to the recent research uncertainty is even more stressful than knowing something bad is definitely going to happen.[1] The study explored how people react to being told they will either "definitely" or "probably" receive a painful electric shock. Intriguingly, the volunteers who knew they would definitely receive a painful electric shock felt calmer and were measurably less agitated than those who were told they only had a 50 percent chance of getting the electric shock. The main finding was that all measures of stress, both subjective and objective, maxed out when uncertainty was highest. When predictability was at 50%, when people had absolutely no clue whether they were about to get shocked, stress peaked.

So, what's the big deal? Everyone knows that uncertainty is stressful. But what's not so obvious is that uncertainty is more stressful than predictable negative consequences. Is it really more stressful wondering whether you'll make it to your meeting on time than knowing you'll be late? More intriguing is the fact that people whose stress responses spiked the most at periods of greatest uncertainty seemed better at guessing the outcome. So it seems like having an uncertainty radar in our brain can actually be seen as survival benefit.[2]

To understand the origin of our natural fear of uncertainty we shall look at the brain's anatomy and physiology. In the next few paragraphs we will even though only schematically and conceptually discuss the different brain structures and their functions, which will help us understand what a change or uncertainty looks like in the brain and why the brain hates it. More interestingly we will learn how to cope with it. The discussion below follows to some extent the lecture course "Introduction to human behavioral biology" given by Prof. Dr. Robert Sapolsky, the neuroscientist, at Stanford University.[3]

While the brain, being arguably the most important organ in the human's body, is insanely complicated (see e.g. brain gross structure in Fig. 1 (a)), there is an over-simplistic and abstract way to think about aspects of brain function, especially when it comes to behavior. This is the concept put forward by Paul McLean, which considers the brain as coming in three functional layers, so called the "triune" brain [Fig. 1 (b)].[4] It is important to stress that even though this model is widely known and also used regularly in e.g. psychology, it is no more than an illustrative schematic and, strictly speaking, it is not entirely correct. (We will also briefly address here why).

This model suggests that the first most, the bottom most part of the brain is what is often termed as reptilian brain. This part is essentially characterized by the same wiring as there was in a lizard or any other ancient creature. And this ancient wiring has been there at the base of the brain, most inside, ever since. This region is known to be responsible for all regulatory stuff, boringly keeping us alive. If the body temperature changes this reptilian brain causes one to shiver or sweat. It monitors our blood glucose level, releases hormones that are essential for everyday life etc. Sitting on top of the reptilian brain is conceptually what is termed a limbic system, that is the emotional part of the brain. And this is pretty much characteristic to mammals, since the emotional life of lizards is not well known. This part of the brain has a lot to do with fear, arousal, anxiety, sexual longing and all sorts of very mammalian behavior. That is what would cause you to be out there on a grass butting heads with someone else if you were a lamb, for example. The reptilian brain is also what stores our habits. Then, sitting on the top is the cortex, which is believed to be the most recently evolved part of the brain, which is thought to be responsible for rational or objective thought, for dreaming, imagining, planning etc.

The original MacLean's model claims that activity in these three brain regions is largely distinct when we are engaged in each of the aforementioned mental activities. For example, when we are in danger and must respond quickly the reptilian structure is aroused, preparing us for action by initiating the release of chemicals throughout the body. When we are watching a shocking news story or receive an upsetting message, the limbic system is stimulated and, again, chemicals are released, which creates our experience of emotions. Finally, when we are making decisions, solving problems or reasoning, the cortex is engaged, without the involvement of the other brain structures. This is exactly where the triune model took a wrong turn. Modern advances in neuroscience (such as brain imaging using e.g. functional MRI) showed that, in fact, various regions of the brain are active during primal, emotional and rational experiences, which led to the rejection of MacLean's notion of a triune brain in neuroscience.[6] Besides, the cortex and its analogues were found in all vertebrates, so it turned out to not be unique to mammals. What's more, all the major structures of the mammal brain can also be found in the reptile brain, and even in the fish brain.[7]

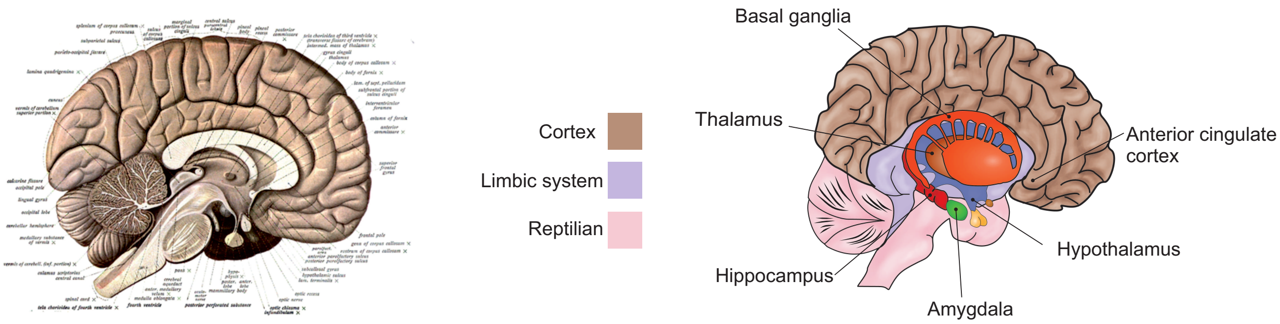

Figure 1: Left: A cross-section showing the gross anatomy of the human brain.[5] Right: Schematic of the brain structure with indicated parts discussed in the text. Note that not all the parts belong to the same cross-sectional plane. The colors indicate approximately the brain regions according to the triune model. Note that the concept of the triune model needs to be considered with care (see text).

Now, keeping this correction in mind, we can think of this simplistic flow of commands with which the layer two, the limbic system could make the layer one, the reptile brain activate. In comparison to the situation where your heart beats faster because of a regulatory reptilian change in your body, i.e. you have been cut and it is painful. Rather, you meet a wild beast and it is threatening you. This emotional state, this fear, causes your limbic system to activate the reptilian brain and your heart beats faster as you have a stress response. Stress response, also called fight-or-flight response, is relevant for the topic of this essay and we consider it more thoroughly now. A part of the brain called amygdala is known to play the primary role here. It is considered to be a part of the limbic system and is known to mediate all the emotional responses (anxiety, fear, aggression).[8]

An environmental stimulus that provokes stress, e.g. various smells, sights, and internal sensations that result in anxiety, triggers amygdala, which sends a distress signal to the hypothalamus. This in turn activates the body's sympathetic nervous system: the adrenal glands release stress hormones like cortisol, adrenaline and noradrenaline.

These circulate through the bloodstream and the brain and have an instant physical effect on our bodies mobilizing energy and facilitating preparation for violent muscular action. These hormones act to increase blood pressure, blood sugar, suppress the immune system and increase the pain threshold (could be quite useful for a fight). Also, the mind becomes extremely focused on the threat which allows the brain to ignore non-relevant information. Thus, the initial response and subsequent reactions are triggered in an effort to create an overall boost of energy which allows one to respond to a threat more effectively in either of the two ways: by attacking the source ("fight") or turning and running away ("flight"). When the threat passes, the levels of the stress hormones fall and the parasympathetic nervous system - the "brake" - sets in to dampen the stress response.

To further complicate things, there are situations where the cortical area commands the limbic system to have an emotional response rather than something physically real and emotional like the beast right in front of you. For example, you see a movie that is emotionally upsetting, and there are no real characters (technically, what you see are pixels), and that is your cortex that is turning this abstract cognitive state into an emotional response. Moreover, the cortex in layer three can even influence layer one: you think "one day my heart is going to stop beating" and your heart starts to beat faster. You are not bleeding and hypotensive, i.e. there is nothing your reptilian brain could logically make sense of. Yet, you can just think of something abstract, i.e. think of someone on the other end of the world you do not even know in person who might be suffering and you feel upset about it and you get the reptilian brain response.

Just as often, though, the opposite, down-up command flow scenario occurs: layer one talks to two, talks to three. An example where your reptilian brain talks to your cortex is the following remarkable finding. When we are hungry, we make harsher moral judgments on other people, we are less charitable.[10] If you feel hunger, if you are in pain etc, affects very much your cortical judgment-type areas. This ancient reptilian part of the brain, which, according to McLean, should have nothing to do with how your cortex works, in fact, has tons to do with it. Or layer two, your limbic system, your emotional state influencing your abstract cognitive processes an obvious example of which is when we are under stress, i.e. in an emotionally aroused state, we often make stupid and impulsive decisions that seem brilliant at that time.

It is also useful to consider the aforementioned brain parts in terms of how much energy they consume. Lucky for us, the region whose job is to keep us alive, the reptilian brain, does not consume much energy. It can be compared to a small motorcycle: it is always active and takes very little energy. And the best thing is that it is completely autonomous. We do not need to think hard how to pace our heartbeat to digest the lunch we just had. The more complex, yet still pretty autonomous, limbic system, which in parts is responsible for our habits, can be compared to an average-size car for the medium amount of energy it requires for its function. It is active most of the time and allows us to be in sort of an autopilot-mode. We manage to do quite well our habitual tasks without thinking too much of what we do, and it saves our brain a lot of energy. Because, in fact, the cortex, our rational thinking part of the brain, is much more energy expensive. Despite a common neuro-myth, that this part of the brain is active sporadically only when needed, cortex is known to be active most of the time. In terms of the vehicle metaphor it is like a plane in comparison with the other brain areas. This also explains why when we are tired or stressed (e.g. after work), and all the energy that we have left is gone to the most important parts, the reptilian brain and the limbic system (at least from the point of view of keeping us alive), we do not make the best decisions, or we are not eager to learn new things, or we may be harsh on our partners and all other things that the cortex has no energy to control at that state.

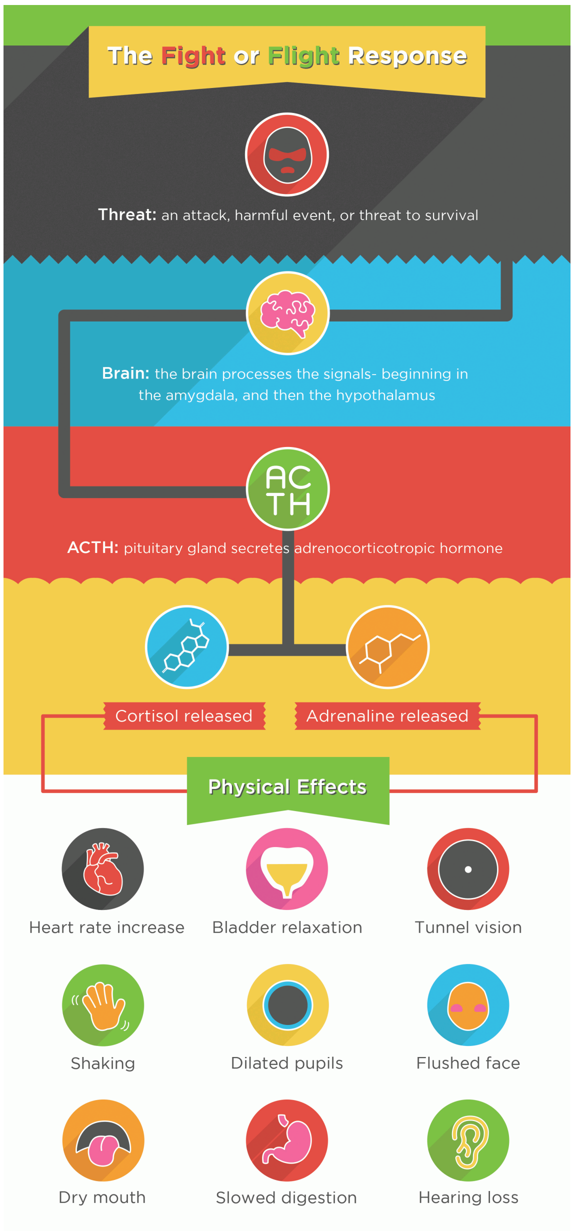

Figure 2: A graphic explaining the fight-or-flight response in humans.[9]

Now, let's get more technical, what does it really mean when neuroscientists say that one part of the brain talks to the other? To communicate, the different brain parts use our body's own electro-chemical messaging system. Schematically, a message starts as an electrical signal traveling down a neuron. When this electrical signal reaches the end of the neuron, some of the neurotransmitters in the terminal are dumped into a nm-sized gap, called a synaptic cleft, between the axon terminal and the dendrite of another neuron (see the illustration of a neuron structure in Fig. 3). This is when the information is transformed from an action potential into a chemical message.

The neurotransmitter crosses the synapse and binds to a certain receptor, on the other side. Each neurotransmitter binds only to its specific receptor, just as a key fits only in a particular lock. And different types of neurotransmitters, e.g. stimulating or inhibiting the other neuron, can make the next neuron either more or less likely to fire an action potential of its own conveying the message forward.

Neural pathways are created in the brain based on our experience. On a microscopic level, the number and strength of synaptic contacts of the participating neurons increases with the frequency a behavior is performed. Besides the number of synaptic contacts, also the involvement of additional brain regions like the cerebellum which causes repeatedly executed actions to become subconscious. The transmission does not really become faster, but it actually takes shortcuts. Thus, with enough repetition, these behaviors become automatic. Reading, driving, and riding a bike are examples of complicated behaviors that we do automatically because neural pathways have formed. In particular, those neural connections in the basal ganglia and motor cortex that have hard-wired a familiar situation with our response to it allow the brain to save its own energy by switching on the "autopilot mode". What it means to the person is that they are free to do multiple things at once, for example, to talk while driving.

But the minute the brain registers ambiguity or confusion, i.e. something that does not fit the expectation of the autopilot brain - if, for example, the car ahead of the driver slams on its brakes - the brain flashes an error signal. This in turn activates the stress response in the amygdala and the same story, the fight-or-flight response described above, begins. With the threat response aroused and working memory diminished, the driver stops talking (except, maybe, shouting out swearing words) and shifts full attention to the road. This error can be caused by any uncertainty, i.e. any contradiction between what our brain expects and what we actually perceive. Even a tiny unexpected thing, like a tree branch moving to your left which your peripheral cortex notices and misinterprets as a potential threat. You have not even had enough time to process it consciously, your amygdala is already triggered and your heart is already racing. The same is true if the change is bigger than that, i.e. in our relationships, society and workplaces, we can also feel threatened, which puts the brain on high alert.

Uncertainty registers[12,13,14] are found in a part of the brain called the *anterior cingulate cortex* (ACC), which is anatomically connected to amygdala so the amygdala[15] immediately gets to know everything that is going on in its neighborhood, e.g. in the ACC. This alone suggests that change can be an emotional process. Not knowing what will happen next can be profoundly debilitating because it requires extra neural energy. This diminishes memory, undermines performance, and disengages people from the present.

That is why people crave certainty. Of course, uncertainty is not necessarily debilitating. Mild uncertainty attracts interest and attention: New and challenging situations create a mild threat response, increasing levels of adrenalin and dopamine just enough to spark curiosity and energize people to solve problems. Moreover, different people respond to uncertainty in the world around them in different ways, depending in part on their existing patterns of thought and the size of their amygdala[13,14] and ACC.[16,17]

But it does not mean that we don't have a say at all in our brain's business. On the contrary, a remarkable property of our brain is its neuroplasticity. Neuroplasticity implies that the adult brain is not entirely "hard-wired" with fixed neuron connections, as it was thought in the beginning. There are many instances of cortical and subcortical rewiring of neuronal circuits in response to training or injury.[18] For example, one of the early works that led to the establishment of this phenomenon reports changes in the brain structure associated with acquiring the knowledge of London's layout in local taxi drivers.[19]

Thus, based on the advances in neuroscience, there are now numbers of different approaches to neurohack our brains being successfully employed in broad range of areas, from medical treatment of mental diseases[20] to leadership trainings in various business companies.[21,22] Now with the help of this short insight into our brains, we can also point out a few milestones that form a fundament for such neurotraining. First of all, if a change is planned, it is important that it is not dramatic right off the bat. Adhering to small steps at a time will help the brain to not ignite the stress response and therefore, the change will be more successful.

From an efficiency point of view, it is recommended to do something new when your brain has enough energy for it. Otherwise it will more likely switch on autopilot and all the hard work done will be in vain. Furthermore, it is not enough to practice every so often. We need to pay attention repeatedly to new actions and insights over a period of time until they become part of how we operate and see ourselves. This is done with the help of our cortex, thus, requiring energy. Most importantly, reinforcing positive change, i.e. associating learning new behaviors with positive emotions will ease the process of change.

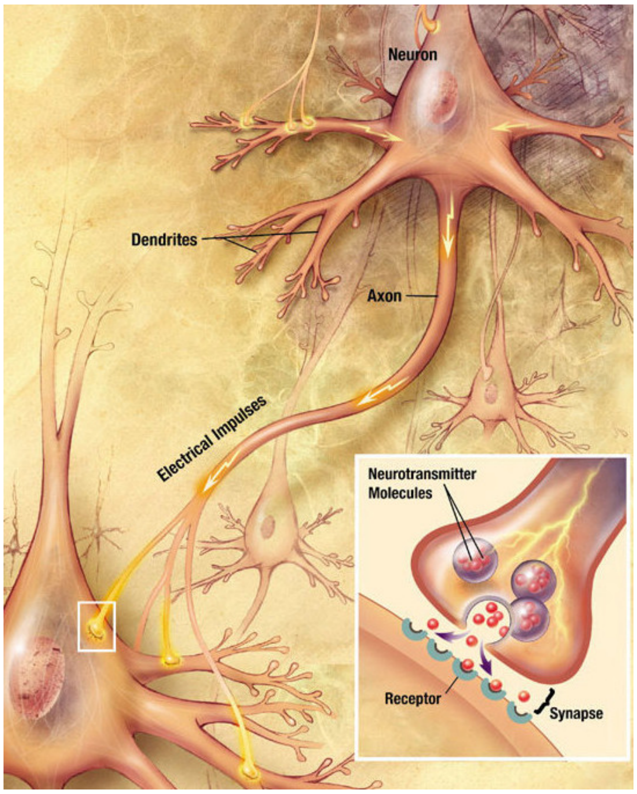

Figure 3: Artistic interpretation of the major elements in chemical synaptic transmission.[11]

In conclusion, while interaction between parts of our brain is a very mechanical process and mostly even unconscious, there is still a lot we can do to change the way it functions. Nobody says it is going to be easy though.

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"You Have to Bend the Rules"

Interview with Sebastian Seiffert on education

Sebastian Seiffert[1] is a professor for physical chemistry of polymers at the Johannes Gutenberg University Mainz. He studied at TU Clausthal during 1999–2004 and completed his dissertation in 2007. After a post-doctoral stay at Harvard during 2009–2010, he headed a junior research group at the Helmholtz-Zentrum Berlin during 2011–2014. During 2014–2016 he was associate professor for supramolecular polymer materials at the FU Berlin. Since 2016 he holds the former chair for physical chemistry of polymers at the JGU Mainz.

Sebastian Seiffert[2] is a professor for physical chemistry of polymers at Johannes Gutenberg University Mainz. He studied at TU Clausthal from 1999–2004 and completed his dissertation in 2007. After a post-doctoral stay at Harvard from 2009–2010, he headed a junior research group at Helmholtz-Zentrum Berlin from 2011–2014. From 2014–2016 he was associate professor for supramolecular polymer materials at FU Berlin. Since 2016 he holds the former chair for physical chemistry of polymers at JGU Mainz.

Sebastian Seiffert developed a keen interest in academic education, teaching and learning already during his time at the TU Clausthal, being a member of the student council. During his stay at Harvard he came into contact with Prof. Eric Mazur and learned about his philosophy of peer instruction[3] which inspired him to further engage with the subject of good teaching. Since then, he has been perpetually questioning the long-established form of frontal lecturing and has been reaching out to make a difference.

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JUnQ: What comes to your mind when thinking about the slogan "Never change a running system"?

Sebastian Seiffert: Did you ever ask yourself what the point of the QWERTY layout of keyboards is? It is a relict from the time of mechanical typewriters. The QWERTY layout ensured that there was less interlocking of letter stamps, as it actually prevents typing too fast by using a purposely ineffective arrangement of keys. With the onset of computers, it would have been logical to overcome that so-far purposely ineffective system and to replace it with a better one. But the concern of non-acceptance by customers, who might be unwilling to adapt to a new system, kept the inefficient QWERTY arrangement in use. In the academic business, especially in its educational branch, we actually follow the same pattern of missing chances for revolutionary improvement quite often.

JUnQ: What was your most frustrating experience regarding this principle?

Sebastian Seiffert: When I was trying a new method for interactive teaching in my class for the first time, I was very eager to implement for the quote that "education is not the filling of a pail, but the lighting of a fire". However, I received reluctant responses from students. I mean, imagine a crowd of students who you try to motivate by confronting them with a new way of teaching, but who are so stuck in old ways of conceiving teaching content that the spark just didn't light the fire. I felt like a fool that day.

JUnQ: Why do you think it is so difficult to make a change in education, especially at university level?

Sebastian Seiffert: There are two elements. One in general is administration. In the academic educational business, there is an external set of rules that dictates exactly how much time you have to spend on teaching, how much time students ought to spend on conceiving it, and even how they have to spend it. Hence, there is not much space for creative approaches if you have to follow this rigid set of rules. The other element is a distinguishing feature to my subject, chemistry. The field of chemistry is, compared to other scientific fields, dominated by conservative views, which also applies to the educational part. In times where flexible and interdisciplinary research is becoming ever more important, this is an unfortunate attitude in my opinion. As a result, I believe that if you want to implement new ways of teaching, you have to try to circumvent or bend the rules, and on top convince your peers frequently.

JUnQ: If there were no boundaries what should teaching look like?

Sebastian Seiffert: Let me answer that with a quote from Eric Mazur that is my general guideline: "Good teaching is to help students learn". We have to create a system which accounts for that. We must motivate our students to learn perpetually and not only excessively before an exam. We also have to create an environment where this continuity is not a surplus of workload but well balanced. How do we get there? Here's a first practical idea: if we implement small five-to-ten minute quick tests at the beginning of every lecture, then the students will have an incentive to dedicate themselves to the content of a lecture beforehand at home. But there has to be enough time for them to do this without overwhelming them with assignments. Ideally, that way, students establish a basic understanding at home and the lecture would let them acquire a more detailed insight later on. This format can also be supported fantastically by using e-learning tools. In that context, make yourself clear that the way we still mostly teach today, the frontal lecture, originates from the 15th century, when books weren't available in mass, so that a privileged person had to read out content to a recipient group. It was the name patron of our university, Johannes Gutenberg, who made books available in mass, which we refer to as the 2nd media revolution. These days, we already experience the 4th media revolution-but apparently, this has not yet reached the academic educational system.

JUnQ: This is remarkable, indeed. But let's get back to your suggestion. Having to write a small exam every week in every course sure creates pressure. How would you avoid this?

Sebastian Seiffert: Let's say if you score less than 50% on average in these quick tests, the only penalty should be that you are not able to score a perfect A or 1.0 in the final exam. That would take away most of the pressure but still ensures an incentive for the motivated students. But also giving the students exact information on where to find the required knowledge via reading assignments helps to lower the barriers for students. A wonderful way is to provide a well written lecture script plus another supporting medium, like an audio podcast or tutorial videos. That way, we can accomplish continuity and reduce exhaustion caused by bulimic learning at the end of the term.

JUnQ: You said that conservative views are sometimes a boundary for progress in education, can you elaborate on that?

Sebastian Seiffert: A key word to understanding this is the term "confirmation bias". For academic teachers, it is very enticing to come to the conclusion that the way they were educated themselves is good because it made them what they are, brilliant researchers and teachers of course. So, questioning the way one was educated appears to be counter-intuitive. And therefore, it is generally difficult to change something. That is also the reason why these discussions tend to get emotional very fast, which makes it even more difficult to progress. A way to circumvent this would be by providing positive incentives like rewarding good attempts and courage in applying new methods in teaching. In addition, I would promote more projects like inverted classroom formats wherever applicable. In my opinion and experience, the best way to realize whether you understood something or not is by explaining it to someone else. So, why not use this exact tool in academic education? - flip the classroom and let students teach each other as often as possible, using written, audio and video teaching materials at home beforehand! Let me repeat: "Good teaching is to help students learn".

JUnQ: Do you have examples on how you have been utilizing these ideas?

Sebastian Seiffert: I like to implement slides in my lectures where I ask a conceptual question, and the students should vote for one out of a couple of answers. If the result suggests that a good share of students got it right, we proceed with the lecture, but if the result suggests that only a minority was able to transfer the knowledge or understand the principle, I will ask them to discuss with their peers for some minutes. Almost every time, a second vote then turns out fine. This method is not invented by me - it is Eric Mazur's "peer instruction" approach, that has been proven to actually work and improve the learning outcome measurably. On top, during the "Corona semester", I provided podcasts plus written scripts in order to provide two channels of knowledge transfer. This was more work for me, but the students appreciated the flexibilty and the way they were able to process the content. But again, I am limited by regulations than supported in being inventive with new ways on how to get the knowledge across.

JUnQ: If it is so difficult from within one could argue that change needs to be induced from the outside.

Sebastian Seiffert: Well no, that is again not as easy. If progress is the aim, the first cogwheels that should turn should be the ones inside the heads of people that are opposing it. Change can only be achieved if enough people believe in it. It cannot be enforced. Take the Corona pandemic as an example. The governmental rules to attenuate the spreading of SARS-CoV2 in spring 2020 were the most severe cuts on individual liberty in the whole history of our republic. But they were carried by the public based on agreement and acceptance. That changed in summer 2020, when shocking pictures of overwhelmed Italian and Spanish hospitals were already forgotten, and the protective means lost public support.

JUnQ: That is an interesting statement especially regarding politics. Do you think this is also the cause for the slow action with respect to climate change?

Sebastian Seiffert: I think there are also other elements. If you look on a political level, the questions are big and vague. Like how do we respond to climate change? There are probably a thousand different answers, which are all correct but none of them could solve the general question by itself. The scientific answer is clear: we must de-carbonize our world economy by the middle of this century. The way of achieving this, however, is a matter of massive debate. It must of course be politically enforced in the end, but this must rest on a solid level of general acceptance in public.

JUnQ: Do you think this makes it difficult for scientists to participate in these processes?

Sebastian Seiffert: Yes, because scientists are trained to raise and answer specific questions one by one. And to proceed by continuous erratum. They are not used to give generally applicable, persistent statements for very complicated questions.

JUnQ: Thinking of climate change or the current corona crisis, is it fear that drives this clinging on the good old days?

Sebastian Seiffert: Most certainly, but not solely. As already mentioned, the confirmation bias also plays a big role here. Many people who have established a comfortable way of living (with a large CO_2 footprint) have indeed earned that by persistent hard work (and by the luck of being born in the first world in the first place), and so they feel that they deserve that way of life. And people who did not suffer from the Corona virus or had no cases in their personal social environment think that everything is fine and do not see a reason for the measures against the virus anymore. In a way, this mixes with the fear that measures imposed on us that affect our daily lives take something away from us without evident benefit. It is hard to grasp climate change or to see an immediate benefit for the environment as an exchange for depriving yourself from something you are used to.

JUnQ: What is your way of dealing with this principle or encountering people who are guided by it?

Sebastian Seiffert: Persistence and esteem. Like in my “peer instruction” games in lectures, I know that the scientific truth will eventually prevail. Even skeptics will eventually see that countries with reasonable means of prevention will do better in the pandemic than others. And they will see that further business as usual will lead to persistent periods of +40 °C in central Europe. I just hope that it won’t be too late for action then.

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JUnQ: What would be your message to all students regarding this subject ?

Sebastian Seiffert: Confucius said “If you make a mistake and do not correct it, this is a second mistake”. I apologize to students that me and my parent’s generation made a terrible mistake and didn’t get the scientific message yet. Dear students, please help us out here. We need you; we need your enthusiasm, your tenacity, and your optimism that everything can be improved.

JUnQ: Thank you very much for the interview!

— Kevin Machel

“Women in Science”

Interview with Dr. Martina Ribar Hestericová

Martina Ribar Hestericová studied biochemistry and bioorganic chemistry at the Comenius University in Bratislava Slovakia and obtained her PhD in chemistry at the University of Basel, Switzerland. She is currently a public relations manager in Lonza Drug Product Services, Basel. Apart from being a scientist, Martina is also an active science communicator (30’000 followers on Instagram[1]), active Twitter account[2] and a science journalist with an important role of changing the perception of women in science[3].

[1]https://instagram.com/science_exercises.eu
[2]https://twitter.com/tatulkaa?lang=en
[3]https://www.priklady.eu/en/hestericova.alej

JUnQ: Where do you come from?

Martina Ribar Hestericová: I am from Slovakia, a country in the middle of Europe full of wonderful people, beautiful mountains, and green forests alive with wildlife.

JUnQ: What is your scientific background?

Martina Ribar Hestericová: I got my Matura at a Gymnasium aimed at natural sciences. After finishing my Bachelor’s degree in biochemistry, I decided to switch by focus and got my Master’s in bioorganic chemistry; my thesis was about solvent-free organocatalysis. I then moved to Switzerland and joined the research group of Prof. Thomas Ward. I was working on the development and optimization of artificial metalloenzymes for nano applications. Last year I defended PhD in chemistry and joined Lonza Drug Product Services as an Associate Principal scientist in forensic chemistry.

JUnQ: How did you discover you wanted to be a scientist?

Martina Ribar Hestericová: My decision-making was quite easy. I fell in love with science already as a small child, my mom would only need to turn on the TV, put on the Discovery Channel and David Attenborough would take care of my attention for hours. I had tremendous luck and got the perfect chemistry teacher when I was about 13 years old. His motivation and enthusiasm convinced me to give Chemistry Olympiad a try. After attending multiple Summer schools of chemistry, I was hooked. Choosing the Uni was quick, I think that I sent only one application letter.

JUnQ: What does being a woman in STEM mean to you?

Martina Ribar Hestericová: I wish for science to be inclusive for everyone, not only women. All minorities should have equal rights, opportunities and conditions. Nevertheless, the situation for women in science, at least in chemistry, is far from ideal. I would prefer to be able to say “I am a scientist”, not “a woman in science”. Unfortunately, women are still underrepresented in science. This is why being a woman in science doesn’t only mean a lot to me, it defines me as a person and as a science communicator.

JUnQ: What is the biggest challenge you face as a woman in STEM?

Martina Ribar Hestericová: My personal biggest challenge is ensuring that my voice is heard without making it sound forced. When I am invited as a speaker on a conference or when it comes to my current job, I am sometimes afraid that some people would assume that I got where I am partly because of my gender - to fit into the statistics.

Secondly, I often encounter girls and women unsure about their potential. It is challenging to convince them about their own worth, but I am trying my best to ensure that they rise above their own limitations and go for their dreams.

JUnQ: How do you spend your free time?

Martina Ribar Hestericová: If I am not writing about science or communicating science, I am reading, running, baking or entertaining our two puppies.

JUnQ: How do you keep a nice equilibrium between your personal and professional life?

Martina Ribar Hestericová: Ever since I finished my PhD studies, I ensure that I take proper care of my well-being and keep my stress levels at a minimum. We all only have one body and one health. Chasing a few more data points will not make a difference in the long run. On the other hand, sleeping enough, eating properly and taking care of your body will.

JUnQ: What/who inspires you and why?

Martina Ribar Hestericová: I get inspired daily by our science communication community on social media. The ideas and effort they put into their posts is just amazing. If we talk about scientists, one of my biggest inspirations - not only because of her research, but also because of her kind personality - is Prof. Frances Arnold (Nobel prize in chemistry laureate).

JUnQ: How was your journey to become a science communicator (writing, speaking, social media, etc). How did you make it happen?

Martina Ribar Hestericová: I initially founded my science-themed Instagram account (@science_exercises.eu) to promote our educational webpage www.science-exercises.eu. I decided to post roughly one picture or video a day to showcase the beauty of science, my research, lab life, science museum - all things related to my life as a researcher. After a couple of months, the profile started to be quite successful. Now, we have almost 30k followers. The same story goes for our Facebook fan page and Twitter account - but here I am also active as a science journalist.

My science journalism started during my PhD studies, I needed to blow off some steam and tried to write a piece for a national newspapers in Slovakia, my home country. I have been writing for them regularly since 2015 now. About 1.5 years ago, I also started writing for international media, such as Physics World, Chemistry World, Physics Today and Education in Chemistry.

The science outreach came along the way, I often take part in outreach events for general public or attend conferences. I do spend my free time on this, but I enjoy it and its importance definitely justifies me not being able to watch my favourite show that often.

JUnQ: How would you explain your STEM field to young girls?

Martina Ribar Hestericová: In my current role, I am working on Extractables and Leachables assessments. These compounds can be extracted from or can leach from materials, which are used during manufacturing drugs. In other words, when you need to take some medication, you take a pill, drink syrup or get a shot. All of these mixtures have to be prepared and during this process, they are in contact with various plastic materials - like tubings, filters, bottles, bags etc. All of these materials can release some chemicals into the mixture and my task is to identify what these compounds are, how much of them is getting into the mixture and if they are safe or not.

JUnQ: From your point of view, how strongly do you feel about actively increasing women's involvement in STEM fields?

Martina Ribar Hestericová: As I said before, I would like to step aside of promoting only women in STEM fields. In my opinion, we are all in the same boat. Anyone should be allowed to become a scientist if they want it. We must ensure that every single underrepresented group or minority, being *lgbtqia+*, women in science, people of any race or religion, or people with disability, feel welcome.

JUnQ: What can be done to promote gender equality in STEM fields?

Martina Ribar Hestericová: I would say that we need more role models for young students. Children often encounter situations in which they would be mocked by their peers for liking biology (boys) or physics / mathematics (girls). If they would know whom to look up to, a living scientist who is fighting these stereotypes, overcoming these obstacles might be much easier for them.

In my opinion, we should really target children, not students at the University. Indeed, there is a leaky pipeline in STEM fields, but before we try to fix that - which obviously needs to be done by the policy of each individual University and/or state, we should ensure, that we motivate enough children of any gender to study science.

JUnQ: What inspirational message/advice would you give any woman to inspire them to pursue STEM?

Martina Ribar Hestericová: Don't let other people's bias and prejudice stop you, believe in yourself and if you have doubts, ask for help. You are not alone!

JUnQ: Thank you very much for the interview!

— Paola Andrea Forero Cortés

"Never Change a Winning Team" - Survey

Tatjana Daenzer

Right? If it runs like a charm, no one wants to improve a process for the worst. But sometimes old habits stick at the expense of progress. This summer, we collected your opinions, experiences, and failures or successes in this specific topic. See what drives our readers:

"The Corona pandemic caused a fierce switch of our work life from the office to home office. Initially, this was no problem, since as a young and adaptable employee, it was not hard for me to master the situation. Especially the advantages of a self-paced everyday life and the omission of commute were valued assets. Nevertheless, after four weeks of a permanent home office, some drawbacks arose. The direct contact with coworkers fell by the wayside. The interdisciplinary communication in the team stopped. Short private chats with witty anecdotes or jokes that ease the everyday work were missing. By self-determining the hours, the start of work shifted first from 7 am to 8 am, then to 9 am, leading to long and slow workdays. Remedy was found by setting up a daily "Corona Home Office"-briefing in the team with fixed time at 7:30 am. The first minutes were even blocked for the so-called "Happy Talk" when we could only talk about everything non-technical. This led to an immense enhancement of productivity in the home office. Recapitulating, in my assessment working at home has many advantages but cannot replace the presence in the office. The after-work feeling is entirely different if you can shut down your notebook in the afternoon and drive home in your car. In the home office, you only move from desk to couch. I recommend a healthy ratio of 50:50!"

Daniel Reichert, automotive sector

"Renewals, improvements always mean a change of old habits. I can mostly report from the commercial handling of our versatile commissions. My business is compartmentalized, meaning that even the smallest unit that comes to our workshop receives its own assignment with its own fixed price. This unit must be handled the same way as a big order, which is processed over a longer timespan with all necessary commercial procedures. Every mouse click counts! We work with SAP. At the end of the day, prepare and process the data for our accounting on-site, so that the evaluation takes as LESS mouse clicks, as necessary. Since the launch of the latest version four years ago, we are cursing because we cannot conduct our daily business - -customer service – the same way the customer is used to. Since last winter, SAP has a new design that cannot be customized by the user. The list view is not user friendly because the chosen line in which we work is not highlighted anymore. I compare new features always with a washing machine with 40 programs but only three are constantly used. Oversizing is the keyword here. The developers brag with their skills but the real use is questionable."

Anonymus

"As a chemist who had to deal with a whole lot of synthesis in her last years, persisting processes that proved themselves to be efficient and expedient, were of huge value for research. It saved a lot of time and energy to rely on state-of-the-art procedures. A slight change can lead to a complete failure of your experiment and the total loss of your material – nothing one would risk lightly. Besides, it is always comfortable to not have to begin from scratch, having to assess every possible procedure and condition. But progress and science live on the audacity to leave your comfort zone, and most of all to be open to new and perhaps bizarre approaches. When I started my doctoral research, my task was to redesign a molecule to make it more potent for certain technical applications. In the industry, a certain synthetic pathway is entrenched and thus, they were stuck. No one had ever thought of reversing this process with just a slight adjustment in the starting material before. The technical setup did not even have to be rearranged. To my relief, the new method worked perfectly and even the resulting substance proved to be more efficient than the state-of-the-art – a dream for young Ph.D. students. Changes do not always mean complete overthrowal of everything that we know but stepping a little bit into the blue and embrace the outcome. Sometimes we fail on the way, sometimes we shine. On a second note, all good things come to an end to make way for even better things. For the upcoming issue, will free the space for a promising member of the editorial board. There will be changes, life-wise and business-wise, but it is nothing to be afraid of!"

Tatjana Dänzer, Ph.D. Chemist

"Most of us have something they want to change. Some want to eat less candy, others want to spend more time with their loved ones, and some want to stop climate change. If the aim is clearly defined and the decision to head for it is made, why is it so often that change does not happen? What I have learned upon change is, that it is a process rather than a single action. Just because it is not implemented right after the resolution, it does not mean that it is never going to happen. For a successful change, one must act in three different areas: 1. Finding support, ideally from people who have considerable influence in the field affected by the change. 2. Resolving conflicts, because there is no change without any. People who defend the status quo for uncountable reasons, e. g. the loss of beloved habits, the fear of the unknown, the depletion of their power. 3. Help others to change their mindsets, because real change is not defined by acting differently, but by thinking in a new way. Even for changes which involve only yourself at the first glance, like reducing your daily amount of candy, it is helpful to keep those three areas of action in mind. Sure, it will take some time to deal with them, but from my experience, your patience and perseverance will be rewarded by a long-lasting change instead of a short-termed behavioral adjustment."

Veronika Beer, chemical association employee

"For technological processes, for example in industry, "if it ain't broke, don't fix it" might hold in some cases. For changes which a society is facing, this is certainly not the best approach. So, let's start with the industry. What makes a company successful? I would say, the key to success is selling products which seem very useful to a large part of the population. Usually, that's because they make life easier (or at least they seem to), e.g. mobile phones. This creates a steady competition for newer products with more or better functionalities. A company with the maxime "never change a running system" will surely by outcompeted very soon. For a society, the same observation holds for a similar reason. A society works well if people feel useful and part of a positive transformation. In my opinion, this is what motivates people and ties the society together. The question here is: Which future are people dreaming of? What would they like to achieve and what are they afraid of? In my impression, for a long time, most people in Germany were wishing for a future without wars and with enough money to be able to afford their own home and hobbies. They were working to improve their life quality and the one of their children. This is what our economy system is still based on. However, now we are at the point where we have more than we need, and working does not improve our life quality anymore. Furthermore, we are facing new challenges, first of all climate change and digitalization. The old driving motivations do not work anymore. We need new visions of a bright future and a way to let people participate. The world is not going to stay the same, but we can influence how it changes. Let's start dreaming and change our future to the better!"

Beatrice Bednarz, Johannes Gutenberg University

"I have been politically active here in Mainz for around 25 years and have experienced time and again that "Never change a running system" is often just the supposedly clever wisdom of maintaining an outdated system. But if we want to improve our society and save the planet, we must also review and change our systems. Nothing has made this clearer to me than my fight against the planned coal-fired power plant in Mainz a few years ago. The climate crisis was already foreseeable then. But the proponents wanted a coal-fired power plant because they were familiar with it and were convinced that the business model with coal-fired electricity would continue to work in the future. But even then it was clear that the economic and ecological conditions had changed. Breaking this mindset was not easy. In 2005, I began to exchange ideas with countless other people, to network and to fight against the planned power plant at all levels - with success in the end: the project was put on hold in 2009and finally buried in 2012. I think that political commitment often arises from the realization that a system cannot remain as it is, that it must be changed, because otherwise it prevents the right course from being set for the future. The Fridays For Future movement was also born out of this awareness: If we do nothing now, the planet will burn us down. Particularly against the background of climate change, melting polar ice caps and extreme droughts, it seems like mockery when decision-makers* inside oppose effective and consistent measures for climate protection with the argument "That was always the case" or "There is nothing we can do about it". A famous quotation, which goes back to the writer Giuseppe Tomasi di Lampedusa, says: "If we want everything to stay as it is, then it is necessary that everything changes". If we want to preserve our earth, we have to change our habits and our laws - and ultimately the whole system."

Tabea Rößner, German Parliament

"The effect of globalization is ubiquitous. It allows for supply chains optimized beyond recognition. My father once asked me how it was possible for producers of printers to produce their machines in a way so that there was still margin left at the low selling prices you encounter on the market. Apart from planned obsolescence caused by actively poor design - this is a whole different story - this is only possible by sourcing the raw materials and assembly workforce at the lowest international price. I.e. these products are mostly not produced in Western countries. Quite the contrary, not only your printer, but also many other products you use on a daily basis have most likely traveled farther than yourself around the globe. That's not a bad thing per se, however, everything comes at a cost. It might not be the currency you have to spend during your purchase, but it might be availability and control. For example, look at the production of pharmaceuticals. Where is it done? About a year ago, it was reported that even the simplest medicines, such as Aspirin or Ibuprofen were partially unavailable. Not mentioning drugs for which the unavailability causes issues greater than prolonged headache. Don't get me wrong, I hardly wish to transform the world back 100 years or so. And I also favor that other countries can develop so that more people get access to the amenities we are so accustomed to we don't even take notice anymore. I love my gadgets! And I can only afford them due to "cost effective" production. But back to availability and control. The first thought which came to my mind when I first heard of Covid-19 was: Will I still be able to purchase my raw materials in China? Can I guarantee steady supply, i.e., allow my employer to produce without interruption at prices allowing to keep our market share? I didn't think this would become a global pandemic. But, terrifyingly, I actually cared more about my supply chain than about the people in China, I must admit. Everything worked out “fine”, mostly due to the supply chain setup I took over, but this whole situation keeps me thinking. Where does that leave us? International production will continue and so will global procurement. However, I think (and hope) that at least for the most essential goods, local alternatives will reappear. Anyhow, this will put us all in places where we need to pay more for the luxury we have and I definitely hope that people will value how good we have it and not take it for granted.”

Andreas Neidlinger, chemical industry

Views on Life, the Universe, and Everything

Questions of the Month

The Journal of Unsolved Questions presents a "Question of the Month" on its homepage every month. Set up and formulated by the members of the editorial board, or guest writers, the main purpose of the "Question of the Month" consists in intriguing the reader by presenting topics of ongoing research. "Questions of the Month" published so far cover a wide variety of scientific fields, but share the feature to be of certain interest to several disciplines.
In the following, we present selected "Questions of the Month" from the last six months.

To progress or not to progress? - Sidenote on Pizza Hawaii -

Kevin Machel
Johannes Gutenberg University, Mainz Germany

In our daily lives, we are confronted now and then if we should do things differently. Even when we speak about benign things like the maintenance of the car and a friend suggests a different way of cleaning it. When we bring food to a party and discuss different ingredients for the same dish. Aside from the discussion about whether or not pineapple belongs on a pizza, how do you objectively determine if it is good to progress, adopt new methods and ideas? In terms of culinary progress, it is evidently easy. Either you like it or not and hence, you progress or not. But when you take decisions on a different level it becomes less simple.

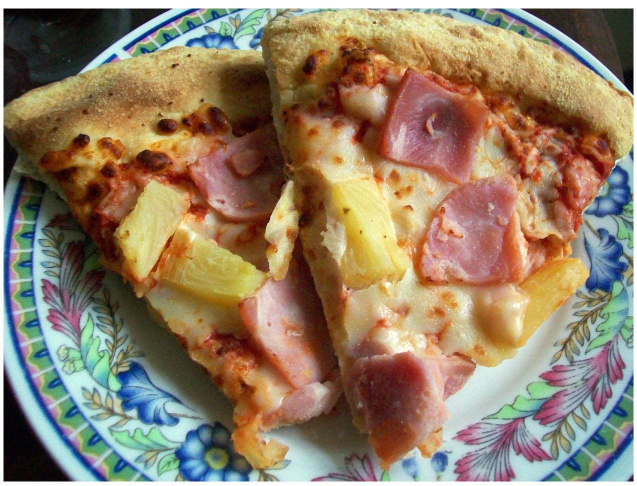

Figure 1: The subject of heated debate, pineapple pizza. Credit:"Project 365 Day 35: Cold pizza" by Peter O'Connor aka anemoneprojectors.

How do you determine if the benefit is worth the effort of restructuring a traffic system of a city or the educational program for a whole country? Discussions on this scale tend to consume a lot of time and energy from people involved and are inherently slow. But how come that big companies determine if it is worthwhile opening up a new store in a city district on a day to day basis? How do traders at the stock market make decisions about the outcome of investment in a matter of seconds and minutes?

Even hundreds of years ago, farmers had to cope with the questions of investment. When considering buying additional livestock, you are confronted with spending more resources and advancing your stables with the prospect of gaining a higher income. Although there might be enough income already, people tend to strive for growth. Hence, these farmers are outweighing the financial effort against the prospective income. As basic as this sounds even today in modern prediction models the same old principle is at work. This process of outweighing effort against benefits can be perceived as a very simple question. What is the minimum effort, that I can undertake, to achieve my goal? The answer to this question then gives us a value or a guideline when or how we should progress.

So what we have is like a linear system with a number of variables that, if solved, yields the value we require to make our decision. And exactly this was the approach by Georg Danzig in 1947.[1] He developed the so-called "Simplex-Algorithm" that is capable of solving such questions with a limited amount of iteration steps. Thereby a complex problem can be disassembled into several variables with different impact factors and processed by this method. [2]

These simplex-algorithms as a subclass of linear optimization processes are essential for the prediction of the economic development of whole countries as well as freight transport and management on a global scale. With modern technology, these models will be able to suggest the quickest, cheapest, or even the most environmentally friendly way of transporting goods, depending on what you prioritize.[3] Since the establishment of such prediction methods a lot of research, development, and refinement produced a wide variety of models using linear optimization, heuristics, or even randomization.

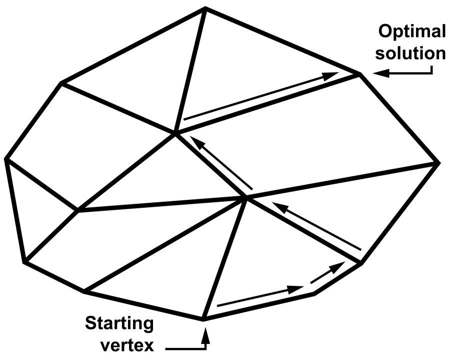

Figure 2: A linear system, that can be regarded as a polytope, is solved by the simplex algorithm trough moving along the edges until it reaches an optimal solution.

This is not surprising considering that some questions are just more complex than others. Take for example the paper-making industry, where a product can have so many different specifications: material, thickness, size, binding, coloration, surface processing, a water sign, and many more options. On top, the manufacturing process is also quite individual depending on the specification of the desired product. There is simply an incredible amount of combinations and therefore variables which to account for.[4]

Therefore, such complex problems have to be divided into groups of problems and subproblems which takes more time and resources to be solved. Besides, straying from the linear dimension of the non-linear optimization enables solving highly complex systems. This, however, can reach a level where people can not even trace back all logical decisions as is already the case for the use of artificial intelligence in stock market decisions. These AIs take a known working approach and refine it to the maximum even for complex systems.[5] On the other hand, a lot of man-made systems also work by this principle. The scientific community in itself is thriving from optimization and advancement aside from answering fundamental questions.

One field that resists vigorously against all approaches for mere rational optimization however is food. What was formerly known as space food (a dry powder that contains all necessary nutrients) is now commercially available in a wide variety.

Figure 3: Exhibit showing the food astronauts ate during the Apollo missions.

But all of these mixtures, that claim to contain all the nutrients in the perfect balance that we need, have one problem in common. The balance of nutrients is based on scientific findings which are just an average and do not account for everyone and they are not definite. There may be nutrients we need that we have not identified yet.[6] Without the addition of aromas they often do not taste even if our taste buds might register the presence of all our required nutrients. On the other hand, taste is highly dependent on nutrients.[7] This makes food a highly complex system with a lot of variables to atone for.

There is a place that just is not always so rational when it comes to decision making and that is our mind. Therefore, it is not surprising that Pizza Hawaii, which can even be nutritionally favorable over some other pizzas, is not as popular.[8,9] Even when considering more variables as pricing, it is a famous example of the irrationality of human decisions, since we simply have different taste and do not always make decisions on a mere objective basis. We base decisions on values we establish for ourselves and a tradition that ensures a good taste might just be more important than experimenting with ingredients on a pizza. This is exactly the weak point of such prediction models since an algorithm might be perfectly capable of suggesting to us the perfect company, living place, and even partner but still fails to really grasp what we expect from life on a personal basis.[10]

In principle, we can say it is always good to embrace progress, but in some regards, it is quite acceptable to stick to your old guns. We can use logical tools like the simplex-algorithm to help us determine the course of very complex systems like governing traffic.[11] But these tools can not ultimately solve the question of what we should eat or how we want to live together as a society. Let alone, what equality means and how we ensure it. These are complex questions that we have to answer the old way by time-consuming but worthwhile debates.

Read More:

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How does Vulture Bee Honey Taste?

Tatjana Daenzer

Most of us love the sweetness of the golden juice that is produced by the ever so sedulous pollen collectors for breakfast, as a sweetener in tea, or as a glaze on roasts. Its origin - be it wildflowers, lavender, acacia or greenflies (yes, forest honey is actually made from honeydew i. e. lice excretion!) - determines the versatile colors and savory flavors of honey. Certain groups of stingless bees belonging to the Trigona genus (T. crassipes, T. necrophaga, and T. hypogea) have almost quit on the traditional diet plan of our vegetarian bees: they receive their protein almost entirely from carrion, meaning that they feed on the flesh of dead animals. Hence the name "vulture bees". With their tiny teeth, 60-80 bees have been observed to reduce the carcass of small reptiles to a skeleton within a day. The meat is partly degraded to mush and flown to the nest where it is ingested and processed by worker bees together with other plant juices to a storable jelly-like material. It has even been reported that some bees break into amphibian eggs or loot abandoned wasp nests with left-behind immature brood.[1]

I did not yet find any hints on how this substance made by vulture bees tastes like. Apart from the problem that there might not be enough substance in one wild nest to obtain a satisfying portion of „carcass honey", the enzymatic process to break down meat is entirely different from breaking down nectar and might result in ingredients that could not agree well with our digestive system. It might not even taste sweet since it is reported to contain about 20% animal protein and would be missing significant amounts of sugar that are otherwise retrieved from the nectar of plants.[3]

Read more:

[1] Mateus S., Noll F. B., *Naturwissenschaften*, **2004**, 91, 94-96.

[2] https://commons.wikimedia.org/wiki/File:Irapu~a-_REFON.jpg

[3] Roubik D. W., *Science*, **1982**, 217, 1059-1060.

Figure 1: The Irapuã bee (T. spinipes), a representative of the Trigona genus. (public domain – wikimedia commons)[2]

Articles

Spin Orientation Manipulation by Electric Fields and X-ray Irradiation

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Electric field-induced strain engineering of the magnetic anisotropy offers a highly attractive perspective for designing future generations of energy-efficient information technologies. In this work, we show using x-ray magnetic imaging and magneto-optic Kerr effect that the applicability of this approach is limited to systems with comparably low magnetic anisotropies or sufficiently large magnetostrictive effect. Furthermore, we find that long x-ray exposure leads to an irreversible change of the magnetic anisotropy in thin ferromagnetic CoFeB films so caution needs to be exercised when analyzing anisotropies. While this change of the anisotropy is shown to be beneficial for the strain-induced manipulation of the magnetic structure, the mechanisms underlying the observed x-ray induced transformation remain an open question. Finally, by directly imaging the magnetic domain structure with gradually varying anisotropy from out-of-plane to in-plane, we observe the impact of strain across the spin-reorientation transition.

1 Introduction

Energy-efficient control of the magnetization state at the nanoscale is fundamental for the future generation of spintronic devices. Conventionally, the magnetization direction of ferromagnetic (FM) elements can be manipulated by electrical currents, required to generate large magnetic fields or spin torques switching the magnetization direction.[1–4] These approaches, however, suffer from significant energy dissipation due to Joule heating. Recently, the use of electric fields to manipulate the magnetic properties has emerged as a promising alternative as it avoids the need for electrical currents.[5]

Although the direct effect of electric fields, e.g. by charge doping, on the magnetic state is often relatively weak,[6] this approach can be mediated by mechanical strain, as it is commonly realized in piezoelectric/FM heterostructures.[7–9] In such systems, an electric field applied across the piezoelectric generates strain, which in turn is transferred onto an adjacent FM. The elastic deformations of the lattice in the FM layer result in the change of its magnetic anisotropy, which is known as the magnetoelastic (ME) effect, due to the ME coupling.[10] The resulting changes of the magnetic anisotropy of the material due to the strain-induced ME anisotropy can be formally expressed as follows:[11]

$$K_{\mathrm{ME}} = -\frac{3}{2}\lambda_s Y \epsilon, \tag{1}$$

where K_{ME} (J m^{-3}) is the ME anisotropy coefficient, λ_s and Y are the magnetostriction constant and the Young's modulus of the material, respectively, and ϵ is the induced strain.

It is known that the strain-induced ME anisotropy in the order of $10-100$ kJ m^{-3} can be achieved for moderate strain magnitudes of $0.1-1\%$[7,12] for some magnetostrictive materials, such as Ni, CoFeB, Ga_xFe_{1-x} films.[11] Thus, for the systems, where other anisotropy contributions are small, the strain effect can be sufficient to modify their magnetic state: for example, to switch the magnetization between an in-plane (IP) and out-of-plane (OOP) orientation under isotropic biaxial strain,[13,14] or rotate within the film plane under uniaxial in-plane strain.[15]

Moreover, the strain-induced changes of magnetic anisotropy result in changes of magnetic structures such

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as spin structures of domain walls,[16] vortices,[7,17] and skyrmions.[18] The dynamic strain can not only drive the magnetic vortex and domain motion,[19] but also modify the mobility of a domain wall driven by conventional magnetic fields and electrical currents.[12,20] Thus, the electric field-induced strain control of magnetic anisotropy is a pathway towards low power tailoring of the magnetic properties of FM thin films and has potential advantages for future generation of magnetic devices.

However, as the strain-induced anisotropy is limited by the magnitude of the generated strain, its impact on the magnetization in the systems with large intrinsic magnetic anisotropies can be insignificant, which, in turn, hinders its observation.

In this work, we first study the effect of piezoelectric strain on the magnetic properties of a W/CoFeB/MgO thin film with a perpendicular magnetic anisotropy (PMA) deposited on a piezoelectric substrate, in the text referred to as "PMA sample" (see Methods for the details on the sample composition). We analyze the magnetization switching behavior by means of magneto-optical Kerr effect (MOKE) and perform direct imaging of the magnetic domain structure as affected by the piezoelectric strain with photoemission electron microscopy combined with x-ray magnetic circular dichroism (XMCD-PEEM). We observe that while the magnetic domain structure of the PMA sample changes locally with a non-deterministic magnetic switching, the macroscopic perpendicular magnetic hysteresis loop of the film, measured with MOKE does not show a large dependence on the applied strain.

We report that during the experiments studying the local spin structure changes using x-ray-based microscopy, an additional mechanism for change of the domain structure was observed: x-ray irradiation induces an irreversible change of the magnetic anisotropy. By comparing the observations on the PMA sample with another PMA system MgO/CoFeB/Ta, grown on a similar piezoelectric substrate (see Methods), initially exhibiting different magnetic properties but demonstrating the same behavior under irradiation, we propose possible mechanisms of the x-ray induced anisotropy change.

Finally, making use of the x-ray induced anisotropy changes we demonstrate the electric field induced strain control of the magnetic domain structure across the region of varying magnetic anisotropy in the samples close to the spin reorientation transition (SRT).

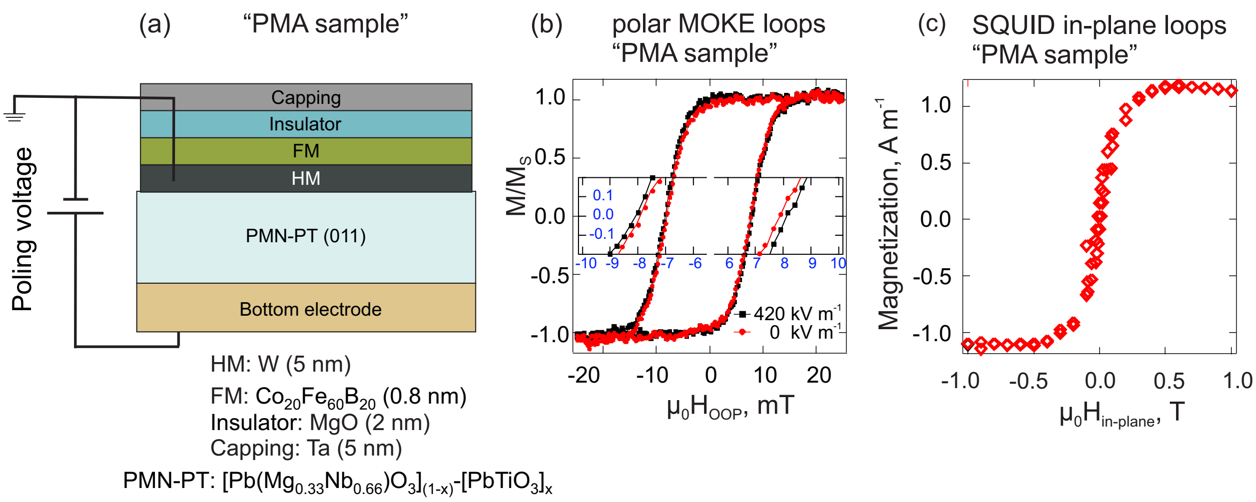

Figure 1: Schematics of the structure of (a) PMN-PT(011)/W(5)/$Co_{20}Fe_{60}B_{20}$(0.8)/MgO(2)/Ta(3) ("PMA sample"). Thickness in parentheses is given in nm. (b) Polar-MOKE hysteresis loops of the PMA sample measured at 0 kV m^{-1} (black) and 440 kV m^{-1}. The MOKE signal was collected from the area defined by the laser beam spot size when focused on the sample surface in a dot of ca. 300 μm in diameter. Note, that the PMN-PT substrate was poled before the measurements, ensuring the linear response of the generated strain to the applied electric field. The inset shows zoomed-in regions of the loops in the vicinity of the coercive fields. (c) In-plane hysteresis loop measured by SQUID for the PMA sample at 0 kV m^{-1}.

2 Electric field induced strain manipulation of the magnetization in PMA sample

To generate the mechanical strain a commercial piezoelectric substrate $[Pb(Mg_{0.33}Nb_{0.66}O_3)]_{0.68}$-$[PbTi_3]_{0.32}$ (PMN-PT) was used.[21] Uniaxial in-plane strain was generated by application of an OOP DC electric field across the piezoelectric PMN-PT(011) substrate. When an electric field is applied along the [011] direction, the compressive and tensile strain along the in-plane [100] and $[01\bar{1}]$ crystallographic directions of the PMN-PT substrate, respectively, are generated.[22,23]

The strain response of PMN-PT (011) to the applied electric field generally exhibits a hysteretic behavior with a large strain jump in the vicinity of the electric coercive field of the crystal (ca. 200 kV m^{-1}).[22] However, a linear regime

with smaller but electrically controllable piezoelectric strain can be used.[7,17] To promote the linear regime the substrate is poled in one direction, by an electric field larger than the coercive field (> 200 kV m^{-1}), and the linear response remains until the substrate is poled in the opposite direction, i.e. as long as the electric field does not exceed the reverse coercive field (< -200 kV m^{-1}).[22] Therefore, prior to the experiments the PMN-PT substrate was electrically poled by applying 400 kV m^{-1} and the measurements were performed using the electric field in the range from -100 kV m^{-1} to 420 kV m^{-1}. From the literature[22,23] it is known that in the linear regime, the piezoelectric coefficients along the $[100]$ and the $[01\bar{1}]$ directions of the PMN-PT substrate are approximately -890 pC N^{-1} and 290 pC N^{-1}, respectively. Furthermore, a finite OOP tensile strain, i.e. along the $[011]$ direction, can be expected based on the volume conservation,[22] which is consistent with the direct measurements by a strain gauge.[23]
The schematic structure of the PMA sample consisting of continuous film of W/$Co_{20}Fe_{60}B_{20}$/MgO/Ta on a PMN-PT (011) substrate (see Methods) is depicted in Fig. 1 (a). Black markers in Fig. 1 (b) show an OOP magnetic hysteresis loop for the PMA sample measured by polar-MOKE. The analyzed area for the MOKE measurements was approximately 300 μm, set by the laser beam spot focused on the sample surface. The hysteresis loop in red was measured under the electric field of 400 kV m^{-1} applied to the PMN-PT (011) substrate. One can see that the shape of the macroscopic hysteresis loop does not qualitatively change upon the application of strain. A slight increase of the coercive field by ca. 0.3 mT, i.e. only 3 % change, upon increasing the electric field can be observed as shown in the inset in Fig. 1 (b). This observation is consistent with the generation of small tensile strain in the OOP direction by application of an electric field as discussed above, which makes the OOP direction more energetically favorable for the magnetization of the CoFeB film with a positive magnetostriction coefficient according to Eq. 1.[25]

The anisotropy constant $K_{\mathrm{eff}} = 0.277$ MJ m^{-3} of the PMA sample was estimated as $K_{\mathrm{eff}} = \frac{\mu_0 H_{\mathrm{k}} M_{\mathrm{s}}}{2}$, where the anisotropy field $\mu_0 H_{\mathrm{k}} = 0.5$ T and the saturation magnetization $M_{\mathrm{s}} = 1.11 \cdot 10^6$ A m^{-1} were extracted from the IP magnetic field sweep shown in Fig. 1 (c) measured by a superconducting quantum interference device (SQUID). It is typical, that for the system with intrinsically large magnetic anisotropies, such as perpendicularly magnetized thin films, the strain needs to be of a much higher magnitude to induce a sizeable relative change in the anisotropy. Typically, strains of a few percent are required, which can only be achieved for example by mechanically bending the substrates.[24]

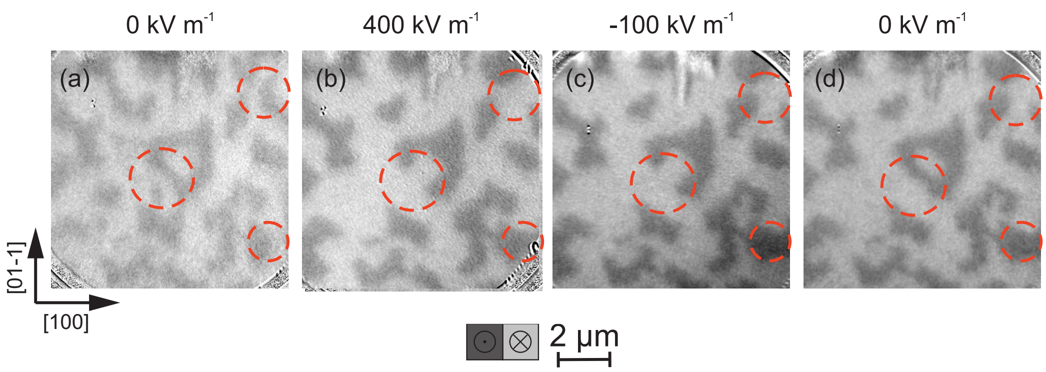

Figure 2: XMCD-PEEM images of the magnetic domain structure of the PMA sample measured at different magnitudes of the applied electric field within the linear regime of the strain response. All images were acquired at zero applied magnetic field. The red circles highlight some areas of the domain structure that switch upon changing the electric field.

However, this does not exclude that local changes of the magnetization can be generated, as previously demonstrated.[26] Figure 2 shows a series of XMCD-PEEM images of the magnetic domain structure of the CoFeB film under an applied electric field of different magnitude and at zero magnetic field. The sample was demagnetized *ex situ* prior to imaging, which led to formation of the OOP stripe domains pattern.

One can see that upon poling the domain structure remains largely unchanged, with only a small fraction of the magnetic domains switching highlighted by red circles in Fig. 2. It is clear by comparing the images in Figs. 2 (a) and (b) that the switching from *up* to *down* as well as from *down* to *up* domains occurs when the electric field is increased from 0 kV m^{-1} to 400 kV m^{-1}. In Fig. 2 (d) we can also see that some parts of the domain structure switch reversibly, but the overall domain structure does not reverse to what it was before poling in Fig. 2 (a).

We also note that the application of an electric field induced-strain does not lead to a reorientation of the magnetization from OOP to IP or *vice versa*, which would result in an additional black/white contrast level in the XMCD-

[2]Similar behavior was observed for a few other points on this sample as well as for other PMA films on PMN-PT substrates, e.g. PMN-PT(011)/W/CoFeB(0.7)/MgO/Ta, PMN-PT(011)/Pt/Co/Pt, PMN-PT(011)/Pt/Ta/Pt/MgO/CoFeB(1.1)/Ta.

PEEM images. Thus, the direct imaging results[2] suggest that most of the observed local changes are random and possibly occur due to strain-induced modification of the energy landscape. On the other hand, a small change in the coercive field seen in MOKE agrees with the observation of some local and reversible changes of the magnetic domain structure.[26]

3 X-ray induced anisotropy change

X-ray induced anisotropy change of the PMA sample As mentioned earlier, the electric field induced strain has a negligible effect on the macroscopic magnetization of the PMA film. However, after several hours of XMCD-PEEM imaging of the PMA sample, we observed that the domain structure started to change, and eventually the OOP domains transformed into a completely different domain structure with a different contrast level. Figure 3 (a) shows a zoomed-out XMCD-PEEM image acquired using a larger field of view (FOV) after this transition. The yellow dashed line indicates the approximate edge of the area exposed by the x-rays during the previous measurement in the FOV 10 μm, for which a high spatial resolution was required (e.g. those shown in Fig. 2). For that the x-ray beam size was reduced by the exit slit of the beamline, so that the footprint of the beam on the sample surface was approximately 10×20 μm set by the instrument.[27]

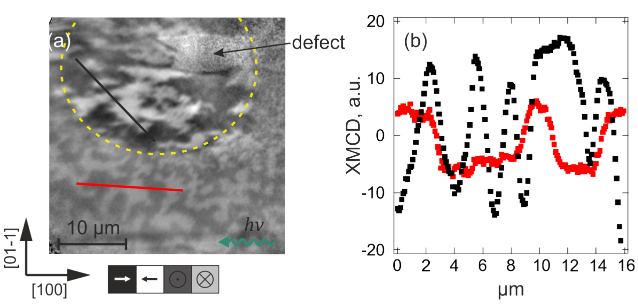

Figure 3: (a) XMCD-PEEM image using FOV of 50 μm after several hours of imaging in FOV of 10 μm showing the domains structure at 0 kV m^{-1} applied across the PMN-PT substrate and at zero applied magnetic field. (b) XMCD signal profiles along the black and red lines, showing that IP and OOP domains yield XMCD contrast of different magnitudes. The crystallographic directions of the PMN-PT substrate setting the tensile ([01$\bar{1}$]) and compressive ([100]) strain directions are indicated.

Thus, the area within the yellow line was exposed by the x-ray beam, and the outer area of the sample was not exposed. We see, that the unexposed region exhibits the same stripe domain structure, while the domain structure of the exposed area is dramatically different. Therefore, we can conclude that the observed local change of the domain structure was caused by the long (ca. 10 hours) exposure by the x-ray beam.

Moreover, the switched area has a noticeably different XMCD contrast level (with a much brighter/darker white/black domains) as compared to that of the OOP stripe domains. This indicates that the domains within the exposed area are more in-plane magnetized, because the low angle of incidence of the x-ray beam leads to a stronger contrast for the IP orientated magnetization. Unfortunately, the additional images corresponding to the different azimuthal angles necessary to extract the angular dependence of the XMCD contrast for these domains could not be acquired, thus we cannot conclude about the exact magnetization direction, which could be tilted between OOP and IP.

On the other hand there is a good agreement with the conclusion that the exposed area has IP magnetized domains from the quantitative comparison of the two XMCD contrast levels measured on the exposed and unexposed regions [see Fig. 3 (b)]. Because the angle of incidence of the x-ray beam is 16° from the surface plane the XMCD signal from the OOP domains should be a factor of $\tan 16^\circ \approx 0.29$ smaller than that from the IP domains, when having the same amount of the spin moment to contribute.[28] We calculate the average maximum XMCD values for the black and red profiles in Fig. 3 (b) and obtain the $\frac{I_{\text{OOP-XMCD}}}{I_{\text{IP-XMCD}}}$ ranging from ~ 0.27 to ~ 0.38. While the former value is approximately equal to $\tan 16^\circ$, which makes the assumption, that the IP magnetization in the irradiated area is along the x-ray direction and in the non-irradiated area it is fully OOP, reasonable, the latter value suggests that the magnetization does not fully lie in-plane. Alternatively, the in-plane magnetization direction may not be strictly along the x-ray beam direction, which would also result in the larger values of $\frac{I_{\text{OOP-XMCD}}}{I_{\text{IP-XMCD}}}$. Nonetheless, from this analysis we can conclude that the magnetization in the irradiated area is tilted from the OOP direction and is close to the in-plane direction.

Another interesting observation is the behavior of the stripe domains close to the exposed area. As seen from Fig. 3 (a), the average stripe domain size gradually decreases approaching the exposed area, where the magnetization lies in-plane. Similar patterns are known for thin wedge systems with a gradient thickness of the FM layer. For such systems the average domain width decreases in the vicinity of a SRT which is attributed to the the variation of the magnetic anisotropy across the thickness.[29–32] As the effective magnetic anisotropy K_{eff} decreases with increasing thickness, formation of domain walls becomes more favorable, because the domain wall energy scales with the anisotropy $\sigma_{\text{DW}} \sim \sqrt{AK_{\text{eff}}}$, where A is the exchange constant, which leads to the increasing number of domains of a smaller width.[29,32]

Based on the observed domain size behavior, we can conclude that in our system spatial variation of the magnetic anisotropy takes place. However, here, the FM layer thickness is homogeneous, therefore a different mechanism needs to be considered, which clearly is induced by the x-ray irradiation.

X-ray induced anisotropy change of the inverted sample Before we go into discussion of the possible origins of the observed behavior, we check if the x-ray induced anisotropy change is limited to this stack or occurs more widely. To this end we study a different material stack, namely Pt/Ta/Pt/MgO/$Co_{20}Fe_{60}B_{20}$/Ta, deposited on the PMN-PT(011) substrate (see Methods). The schematic structure of this sample is shown in Fig. 4 (a). Note that the order of the layers is inverted as compared to that of the previously discussed PMA system, thus we term this sample in the description below as “inverted”. Here we also find a similar x-ray induced anisotropy change.

MOKE and SQUID magnetometry results, presented in Figs. 4 (b) and (c), respectively, show that in the inverted sample the PMA ($K_{\text{eff}} \approx 0.1$ MJ m^{-3}) is reduced as compared to the Ta-based stacks with a conventional order of the layers[33] and the PMA sample discussed above, thus, it is already close to the SRT before the x-ray exposure.

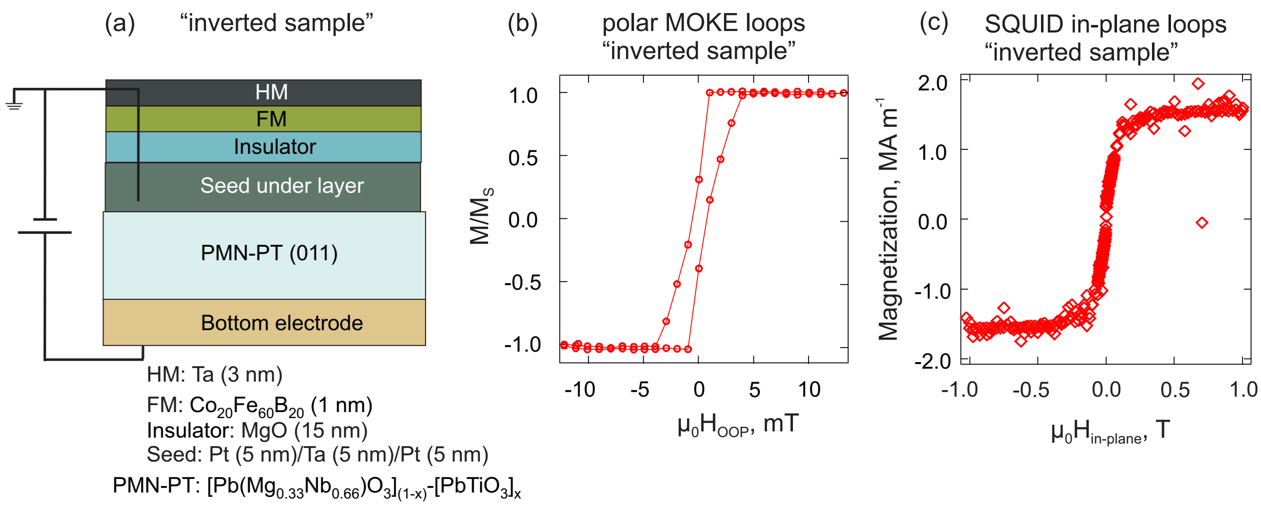

Figure 4: (a) Schematics of the structure of PMN-PT(011)/Pt(5)/Ta(5)/Pt(5)/MgO(15)/$Co_{20}Fe_{60}B_{20}$(1)/Ta(3) (“inverted sample”). Thickness in parentheses is given in nm. (b) Polar-MOKE hysteresis loops of the inverted sample measured at 0 kV m^{-1}. The MOKE signal was collected from ca. 300 μm of the sample surface, that is the laser beam spot size when focused on the sample surface. (c) In-plane hysteresis loop measured by SQUID for the inverted sample at 0 kV m^{-1}.

Prior to XMCD-PEEM imaging the inverted sample was demagnetized *ex situ* and the magnetic field was set to zero during the measurements. The domain structure of the inverted sample is shown in Fig. 5 (a), and resembles a regular stripe domain structure with an average domain size of $300 - 400$ nm. With the x-ray exposure, the domain pattern disappears following the noticeable reduction of the stripe domain width. This suggests that the domains become smaller than the accessible resolution of the instrument (ca. 60 nm in XMCD mode using 10 μm FOV).

The stripe domains disappear completely after ca. 20 s of the x-ray exposure, and after ca. 200 s the new domain structure, exhibiting a stronger XMCD contrast, starts to propagate from one edge of the FOV [Fig. 5 (b)]. Note that the x-ray beam was intentionally put off the center of the FOV, thus, leading to a photon flux gradient. Switching off the x-rays for some time did not lead to recovery of the initial stripe domain phase, suggesting the same irreversible character of the x-ray induced changes of the magnetic properties, as discussed above for the PMA sample studied first.

In Fig. 5 (b) it is also possible to see that the new domains start propagating from one side of the image, i.e. from the maximum of the x-ray beam intensity. This suggests that the x-ray flux indeed governs the process. The switching occurs more readily at higher intensity of x-rays and then propagates to the edges of the beam, where the flux drops strongly.

We also note, that in this case the resulting domain structure formed with the time of the x-ray exposure clearly resembles the ferroelectric domain structure of the PMN-PT substrate known from the literature.[22] Also, similarly to the PMA system, the XMCD contrast of the stripe domains [Fig. 5 (a)] is a factor of 3 smaller than that after the irradiation-induced switching [Fig. 5 (c)], which suggests that the newly formed domains are more in-plane magnetized. Moreover, the new domains here appear only bright or dark, with no noticeable contribution of gray domains (with the magnetization perpendicular to the x-rays propagation direction). Thus, the switched area exhibits an easy axis along the x-ray direction or along one of the crystallographic axes of the cubic PMN-PT substrate.

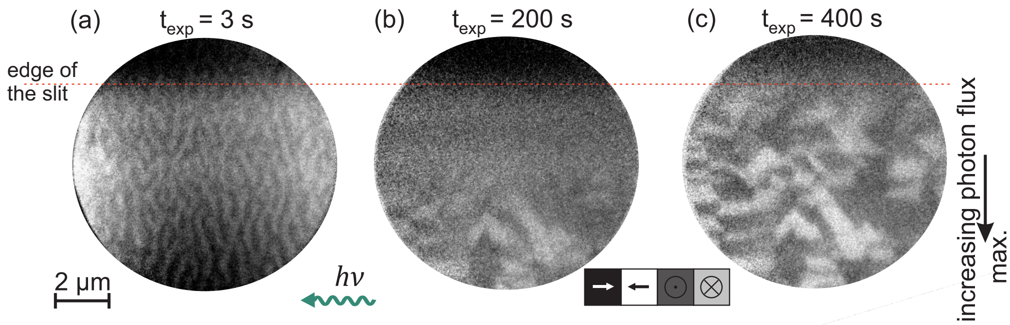

Figure 5: Snapshots of XMCD-PEEM imaging of domain structure of the inverted sample, acquired after different x-ray exposure times t_{exp} at 0 kV m^{-1} applied across the PMN-PT substrate and at zero applied magnetic field. Note that the black/white contrast in (a) is enhanced on purpose for better visibility of the domains.

4 Possible origins of x-ray induced anisotropy modification

It is known, that x-ray irradiation can alter the charge and orbital states of strongly correlated systems[34–36] and perturb the bonds of soft materials.[37] However, the materials studied here are expected to be neither of these. On the other hand, it is also known from the literature that high-energy x-rays and secondary electrons generated due to the photoeffect have a strong effect on insulating materials,[38] which compose a significant part of the systems discussed in this work (PMN-PT substrates and MgO layers are insulating). The processes which are expected to be responsible for the x-ray induced damage, can be classified as follows: (*i*) the ones which occur during the transport of the exited electrons in the material and (*ii*) those, due to the electrons emission into the vacuum.

For the former, it was shown that the core electrons/holes excited by x-rays can scatter with ions in the insulating oxide-containing layer, which leads to breaking the bonds and subsequent creation of structural defects, especially oxygen vacancies.[39] The latter leads to local charging of the irradiated area, because many electrons are emitted into vacuum. While in conductive materials, the lack of electrons is compensated within a few picoseconds,[40] in the case of insulating materials the recombination rate is strongly suppressed. Thus, the resulting uncompensated electric field can drive the migration of the mobile ions in the sample.[38,41] Moreover, the ion desorption cannot be neglected when the electric field strength is large and the electrons coming from the surroundings cannot compensate for the emission of the electrons in order to reach a stable electrostatic equilibrium.[41] On top of this, according to previous studies, also the local heating due to the deposited energy by x-rays leads to an enhanced drift and diffusion of oxygen within the system.[42] The diffusion of interstitial ions was shown in the literature to take place even at room temperature, which can lead to their aggregation into clusters, which become more stable with the size of the clusters, resulting in long-lived local structural deformations.[43]

The aforementioned processes could be relevant for our systems because the magnetic anisotropy in these stacks, originating from both interfaces of the magnetic CoFeB layer, is determined by the surrounding of the magnetic atoms. The origin of the interfacial PMA in the FM/MgO interface is partially attributed to the interfacial symmetry breaking and the hybridization between Fe(Co) $3d$ and O $2p$ orbitals.[44,45] On the other hand, the contribution from the heavy metal to the PMA is due to hybridization of both d and p orbitals at the interface via spin-orbit coupling.[46,47]

From these arguments it becomes clear that any structural modification of the interface will affect the interface-induced magnetic anisotropy. For example, it was shown that the PMA in Co/Pt systems can be altered by irradiation of the samples with He^+ or Ga^+ ions with the energies of several tens keV.[48–50] The observed behavior was attributed to the irradiation-induced short-range displacement of recoil atoms and their relaxation to new positions with local surroundings differing from their initial one,[49] which in the case of interfacial atoms, resulted in a change of the PMA in Co/Pt systems. Furthermore, ion irradiation was also shown to cause intermixing between Co and Pt in such systems, which, in turn, can result in an in-plane lattice expansion and the anisotropy change via the ME effect.[49] While on our experiment no ion irradiation was employed, x-ray irradiation-induced processes leading to local structural deformations of the MgO layer and its interface with CoFeB, could still take place, as discussed above. Therefore, we can apply similar arguments to explain the change of the magnetic anisotropy in our system.

Alternatively, recent studies report voltage control magnetic anisotropy (VCMA), which is realized when a voltage is applied across an thin oxide/FM interface.[51] This leads to a charge redistribution between the OOP and IP orbital of the FM, resulting in the change of the surface magnetic anisotropy.[45]

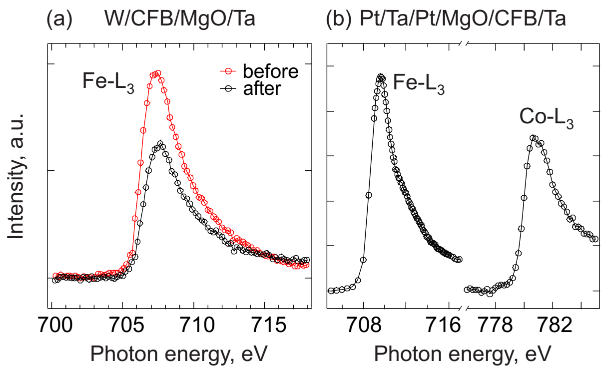

Figure 6: (a) X-ray absorption spectra (XAS) corresponding to the Fe L_3 absorption edge measured on the damaged area for the PMA sample before and after the x-ray induced SRT. (b) XAS for Fe and Co measured for the inverted sample after the exposure that leads to the reorientation of the magnetization in to the plane.

Thus, taking these facts into account we can expect that any structural or electronic change in the vicinity of the two CoFeB interfaces due to the x-ray exposure can alter the magnetic anisotropy of the system, which results in a change of the domain structure. Now we can go through the arguments, that allow us to rule out certain scenarios seemingly responsible for the observed behavior of our systems.

(*i*) Based on the shapes of the Fe and Co absorption peaks shown in Fig. 6, which were measured on the exposed area after its OOP-IP transition, we can exclude significant oxygen implantation into the CoFeB layer. In the case of Fe or Co oxidation a typical oxide shoulder feature would appear in the corresponding peaks. However, the spectra in Fig. 6 (a) do not indicate any formation of an iron oxide peak in the PMA system. Only a slight change in the intensity is observed, which can be attributed to the carbon deposition due to x-ray induced contamination.[52] Presented in Fig. 6 (b) Fe and Co absorption edges of the inverted system, corresponding to the switched area,[3] also do not exhibit oxide features.

(*ii*) As a result of the irradiation-induced ion migration, oxygen ions could also leave the MgO layer and diffuse into the adjacent non-magnetic metallic layer (for example, Ta for the PMA sample).[4] It is important to point out that a nominally similar stack as that used for the inverted sample, grown on a conductive Si substrate with only a thin natural SiO_2 layer, did not show any x-ray induced damage/change within a few days of exposure with similar photon flux. This suggests that an insulating PMN-PT substrate which also has plenty of oxygen indeed plays a role in the irradiation damage. On the other hand, this scenario could explain the local change of the anisotropy in the PMA sample.

(*iii*) It is important to keep in mind that during PEEM imaging, the sample surface is always electrically grounded [Fig. 1 (a) and (b)]. To ensure a good electrical contact the multilayer stack, containing a thick insulating MgO layer, was scratched at the sides and a drop of conducting silver paste is used to attach the sample to the sample holder body (local ground of the microscope). Therefore, all of the metallic layers on top of PMN-PT are expected to be on the same (ground) potential. Thus, the excess of positive charge due to emission of secondary electrons, can potentially be easily compensated by the conduction electrons from the metallic layers.

Below we summarize the observations discussed above, which, however, did not bring us to a conclusive understanding of the mechanisms underlying the x-ray induced OOP to IP SRT:

- The x-ray induced anisotropy modulation starts from the area with a higher photon flux;
- The anisotropy change occurs on different time scales for the PMA sample (with higher PMA, ca. 10^4 s) and for the inverted sample (with canted magnetization, ca. 200 s) for a comparable photon flux;
- Induced IP domains have a magnetic easy axis along x-rays or crystallographic directions of the PMN-PT substrate. Note that circularly polarized light was used, i.e. no defined electric field direction could be imposed on the domain structure;
- A gradual change of the domain structure is observed indicating a gradual change of the anisotropy;
- The sample surface is always electrically grounded providing a source of electrons to prevent charging;
- Fe, Co peaks do not have features typical for oxides within the resolution;
- Demagnetization of the samples by cycling an external magnetic field does not help to recover the stripe domain phase, signifying a permanent structural character of the x-ray induced changes;
- For inverted stack grown on Si/SiO_2 substrate the x-ray induced SRT does not occur within (at least) 3 days of exposure.

Despite the argument that the sample surface is always grounded, the most plausible mechanism of the x-ray induced SRT in our system relies on local charging due to the lack of the electrons and inability of thin conductive layer as compared to an insulating bulk to compensate for this. This charging, leading either to the displacement of ions as well as local charge redistribution on the orbitals at the CoFeB interface which determine the magnetic anisotropy of the systems, results in the decrease of the PMA and the associated OOP to IP transition.

[3] The SRT occurs much faster (ca. 20 s) than the time necessary to acquire one XAS (ca. 5 min).
[4] The absorption peak of Mg after the SRT was not measured.

5 Strain induced changes of the domain structure close to the SRT

In this section, we consider again the PMA sample, where we can take advantage of the modified magnetic anisotropy by the x-ray exposure to be sensitive to small strain-induced anisotropy change. The irradiated areas allow us to simultaneously investigate the impact of strain on the domain structure at the regions with different magnetic anisotropies, from IP to OOP. As discussed above, the electric field induced strain does not influence the OOP domain structure. However, as in the region close to the SRT, the magnetization is canted from the OOP direction, a larger effect of strain on the domain structure can be expected. It is important to note that while the absolute strain-induced anisotropy change is the same, close to the SRT, where the anisotropy is suppressed, the relative effect on the magnetization alignment is larger.

Figure 7 shows a series of XMCD-PEEM images of the area close to the SRT, including the OOP and IP magnetized regions. We can see that the entire IP region changes contrast from black/white to gray, while the OOP region remains the same. The observed change is mostly reversible and volatile, i.e. when the electric field is removed, the domain structure changes again, but with a new distribution of the domains. While the individual domains do not switch to the original state after removing the electric field, the magnetic anisotropy favoring black and white IP domain recovers.

We also note that the border between the IP and the OOP magnetized regions at 0 kV m^{-1} shifts by a few μm after the first electric field cycle (0-400-0 kV m^{-1}). But it stays nearly at the same place after the second field cycle (0-500-0 kV m^{-1}). However, it is not straightforward to conclude whether this is induced by strain or by the x-ray exposure.

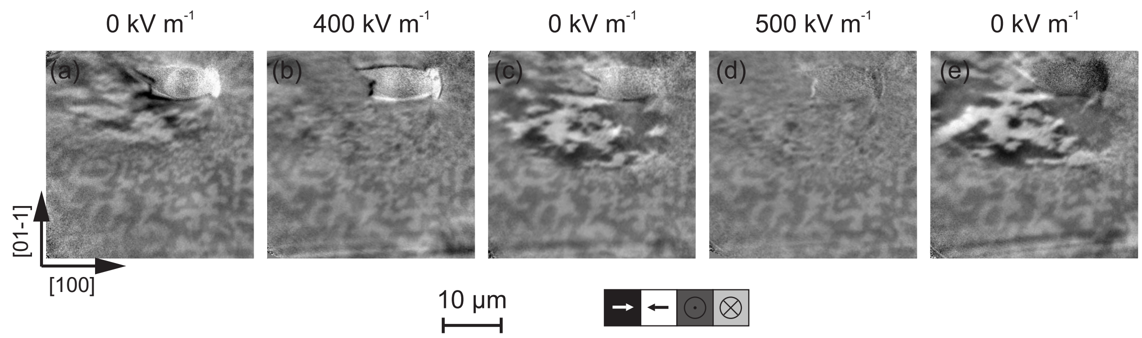

Figure 7: Set of XMCD-PEEM figures of the domain structure of the PMA sample, where part of the FOV underwent a SRT due to the x-ray exposure, acquired at different magnitudes of the applied electric field across the PMN-PT substrate. All images were acquired at zero applied magnetic field. The crystallographic directions of the PMN-PT substrate setting the tensile ($[01\bar{1}]$) and compressive ($[100]$) strain directions are indicated.

To analyze in more detail the character of the strain induced switching observed in the IP region, we quantitatively consider the change of the XMCD contrast of the individual domains in the images in Fig. 7. The results are summarized in Fig. 8 (a), where the XMCD contrast as a function of the cycling electric field is plotted for several areas. All analyzed areas are indicated in Fig. 8 (b) and Fig. 8 (c) shows zoomed-in regions of the considered domains. The value of the XMCD contrast was calculated as the average over a selected area corresponding to one domain at all values of the electric field.[5]

Here we can see that at least five distinct states can be differentiated from the contrast, which are shown shaded in Fig. 8 (a), i.e. IP-white, IP-black, OOP-bright, OOP-dark and IP-gray. The latter corresponds to the domains with the magnetization perpendicular to the x-ray direction, which yields zero XMCD contrast.

In Fig. 8 we can observe random switching of the IP domains to OOP (corresponding to IP-white to OOP-bright switching events) or 90° rotation of the IP domains (corresponding to IP-white to IP-gray switching events) in the regions in the vicinity of the domain walls. On the other hand, it can be seen that the magnetization in the middle of a domain at 0 kV m^{-1} (e.g. region "3"), is likely to remain not switched upon application of strain. This may be an indication of the inhomogeneities within the irradiated area, i.e. local pinning sites or the induced strain inhomogeneities,[8] leading to locally varying magnetic anisotropy. Thus, for some domains the generated ME anisotropy is enough to alter the magnetization state, while it is not for the others. For comparison, we also plot the XMCD contrast evaluated for non-irradiated areas "6" and "7", which do not show any variation with the electric field strength and provide a reference for the OOP-bright and OOP-dark levels indicated in Fig. 8 (a).

Moreover, the global behavior of the domain structure within the irradiated area, i.e. where the PMA is strongly suppressed, is consistent with that governed by the ME effect. As the initial state at zero strain (i.e. 0 kV m^{-1}) is mostly IP magnetized, the generation of strain (compressive along the $[100]$ and tensile along the $[01\bar{1}]$ and $[011]$ directions) upon increasing the electric field leads to cant-

[5] Within these areas the mean deviations were not larger than 10%, thus ensuring the pixels belong to the same domain at each electric field value.

ing of the magnetization of the CoFeB layer with a positive magnetostriction coefficient to the OOP direction (or its 90° rotation in-plane towards the tensile direction). Thus, the domain structure at 400 kV m^{-1} and 550 kV m^{-1} [Figs. 7 (b) and (d)] looks mostly gray with either small OOP domains or IP domains with the magnetization perpendicular to the x-ray direction.

We also note that unfortunately due to small size of the irradiated area demonstrating the SRT, we could not find the same spot in MOKE to study directly the impact of the strain on the magnetic anisotropy by corresponding magnetometry measurements.

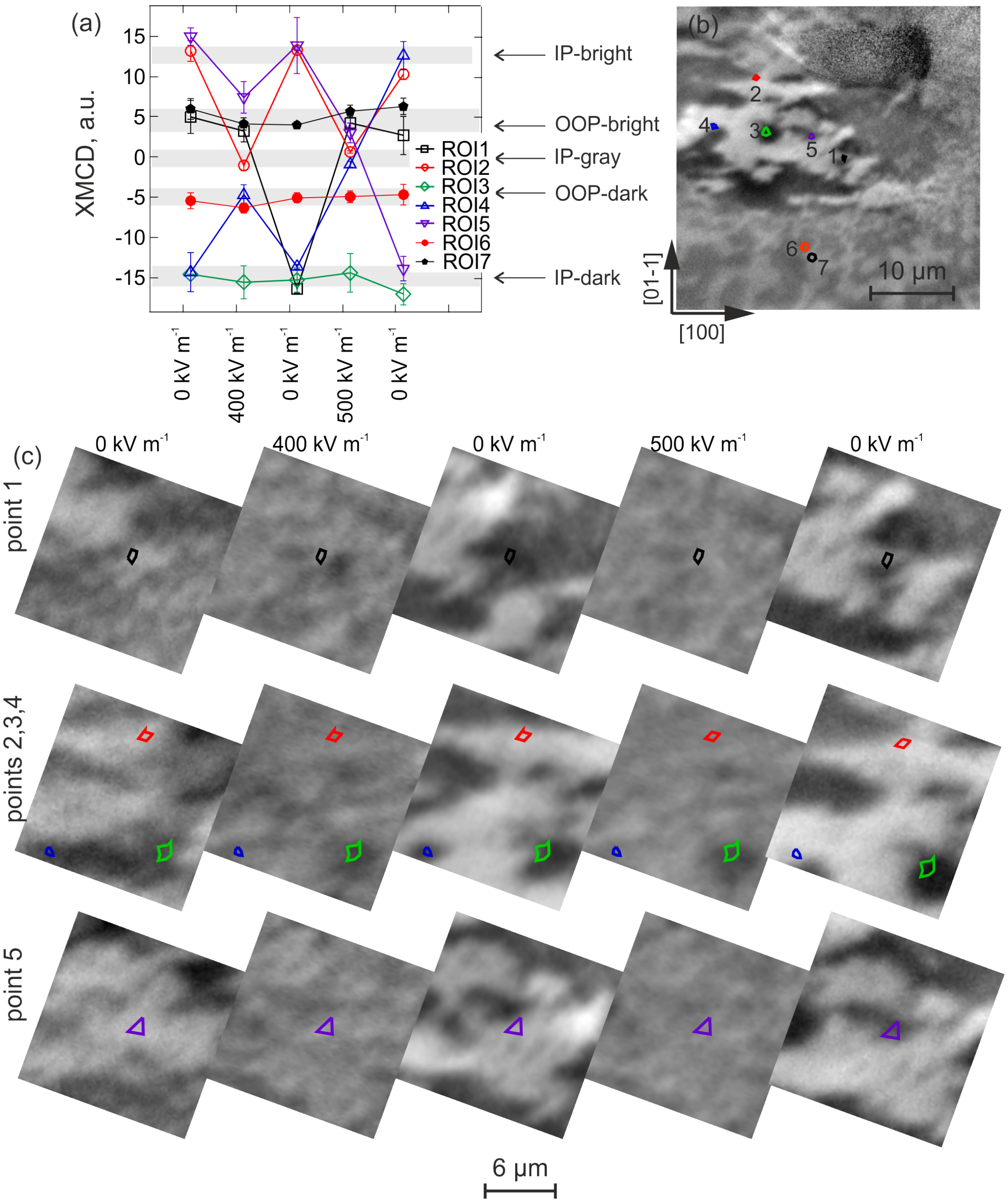

Figure 8: (a) XMCD contrast of the selected regions entailed by the magnetic domains of the PMA sample, showing the strain induced switching between five possible magnetization directions. (b) The same as in Fig. 7 (e) XMCD-PEEM image showing all analyzed in (a) regions. (c) The same as in Fig. 7 zoomed-in XMCD-PEEM images showing in detail the analyzed in (a) regions.

6 Conclusions

In conclusion, while the small impact of strain on the macroscopic perpendicular magnetic state of the PMA sample measured by the hysteresis loop did not come as a surprise, the x-ray induced modulation of the magnetic anisotropy observed for both the PMA sample and the inverted sample, is unexpected. As a result of this irreversible effect of the x-ray exposure, the domain structure of the irradiated region of the PMA sample indicates that the effective magnetic anisotropy of the system is gradually changing from an easy perpendicular axis to an easy in-plane anisotropytowards the region exposed with the highest photon flux. On the contrary, the magnetic anisotropy of the unexposed area did not change. The attempt to explain this spatially inhomogeneous magnetic anisotropy variation, which clearly was induced by the x-ray irradiation, did not allow us to conclude on a clear mechanism. However, the resulting gradient of the magnetic anisotropy on such a small length scale allowed us to observe the effect of the strain induced ME anisotropy on the magnetic domain structure, where the strain-induced K_{ME} comparable to the effective anisotropy of the film was able to alter its magnetization state.

7 Methods

W(5)/$Co_{20}Fe_{60}B_{20}$(0.8)/MgO(2)/Ta(5) continuous films, referred to as *PMA sample*, and Pt(5)/Ta(5)/Pt(5)/MgO(15)/ $Co_{20}Fe_{60}B_{20}$(1)/Ta(3), referred to as *inverted sample*, were sputter-deposited on top of a bare unpoled two-sides polished piezoelectric PMN-PT(011) substrate. Here and below the thickness in parentheses is in nm.The bottom contact of Cr(5)/Au(50) was deposited by DC sputtering in Ar atmosphere. Before the XMCD-PEEM and MOKE measurements the PMN-PT substrates with already deposited films were electrically poled by applying 400 kV m^{-1} across the substrate to promote the linear response regime of the generated strain. During the experiments the electric field was ranging from -100 kV m^{-1} to 420 kV m^{-1}, thus not exceeding the opposite electric coercive field.

Part of the experiments were carried out at SIM beamline of Swiss Light Source (SLS) as well as at UE49-PGM beamline of Helmholtz-Zentrum Berlin (Bessy). The samples were illuminated by circularly polarized x-ray beam at $16°$ angle of incidence. For XMCD-PEEM imaging the photon energy was set to 708 eV and 710 eV corresponding to the Fe L_3 absorption peak for the PMA sample and the inverted sample, respectively. The secondary electrons were detected by a commercial PEEM/LEEM setup. XMCD-PEEM images were obtained using the formula for the asymmetry $\frac{(I_+-I_-)}{(I_++I_-)}$, which is proportional to $\cos\alpha$, where α is the angle between the directions of the incident circularly polarized x-rays and the film magnetization. $I_{+(-)}$ are the images acquired with circular positive (negative) polarization of the x-rays. All XMCD-PEEM images were acquired at zero magnetic field.

XMCD-PEEM imaging of the PMA sample was carried out at Bessy with a nominal x-rays beam flux at 1 keV of approximately 5×10^{13} photons/s/100mA.[53] The inverted sample was imaged at SLS with a flux of approximately 2.5×10^{14} photons/s/100mA.[54]

Prior to XMCD-PEEM imaging of the PMA sample the Ta capping layer was partially removed *in situ* by Ar^+ sputtering at the Ar pressure inside the chamber of 5×10^{-5} and the energy of 1 kV for 30 minutes. Based on the sputtering rate calibrations, ca. 2 nm of Ta were removed, which was sufficient to probe the underlying CoFeB layer without altering its magnetic properties. For the inverted sample this procedure was not necessary, as the Fe absorption edge was sufficiently intense (ca. 30%) to obtain a reasonable XMCD contrast.

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