KIT SCIENTIFIC REPORTS 7754

Annual Report 2017

Institute for Pulsed Power and Microwave Technology
Institut für Hochleistungsimpuls- und Mikrowellentechnik

John Jelonnek (Ed.)

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Edited by
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Institute for Pulsed Power and Microwave Technology (IHM)

Institut für Hochleistungsimpuls- und Mikrowellentechnik (IHM)

Director: Prof. Dr.-Ing. John Jelonnek

The Institute for Pulsed Power and Microwave Technology (Institut für Hochleistungsimpuls- und Mikrowellentechnik (IHM)) is doing research in the areas of pulsed power and high-power microwave technologies. Both, research and development of high power sources as well as related applications are in the focus. Applications for pulsed power technologies are ranging from materials processing to bioelectrics. High power microwave technologies are focusing on RF sources (gyrotrons) for electron cyclotron resonance heating of magnetically confined plasmas and on applications for materials processing at microwave frequencies.

The IHM is doing research, development, academic education, and, in collaboration with the KIT Division IMA and industrial partners, the technology transfer. The IHM is focusing on the long term research goals of the German Helmholtz Association (HGF). During the ongoing program oriented research period (POF3) of HGF (2015 – 2020), IHM is working in the research field ENERGY. Research projects are running within following four HGF programs: "Energy Efficiency, Materials and Resources (EMR)"; "Nuclear Fusion (FUSION)", "Nuclear Waste Management, Safety and Radiation Research (NUSAFE)" and "Renewable Energies (RE)".

During 2017, R&D work has been done in the following areas: fundamental theoretical and experimental research on the generation of intense electron beams, strong electromagnetic fields and their interaction with biomass, materials and plasmas; application of those methods in the areas of energy production through controlled thermonuclear fusion in magnetically confined plasmas, in material processing and in energy technology.

Mentioned long-term research areas require the profound knowledge on modern electron beam optics, high power micro- and millimeter waves, sub-THz technologies, vacuum electronics, material technologies, high voltage technologies and high voltage measurement techniques.

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1 Nuclear Fusion (FUSION): Plasma Heating Systems -Microwave Plasma Heating & Current Drive Systems-

Contact: Dr. Gerd Gantenbein

The Department for High Power Microwave Technologies is focusing on the research and development of high power RF sources (gyrotrons) and related components for electron cyclotron resonance heating and current drive (ECRH&CD) of magnetically confined nuclear fusion plasmas.

In particular the following major activities have been carried out in 2017:

- Gyrotron Development for W7-X, targeting at 1.5 MW RF power at 140 GHz.
- Experimental study on further performance optimization of the European 1 MW, 170 GHz Hollow-Cavity Gyrotron Prototype for ITER.
- 2 MW, 170 GHz Longer Pulse Coaxial-Cavity Gyrotron Prototype, upgrade of the modular short pulse gyrotron with internal cooling systems.
- Gyrotron Development for DEMO, with the focus of efficiency enhancement by multi-staged depressed collectors.
- Developments on theory and numerical simulations of beam-wave interaction tools, electron beam-optics codes and quasi-optical systems.
- FULGOR: progress in the erection of the new gyrotron test stand
- Generation of ultrashort pulses using advanced gyro-TWT design.

1.1 Gyrotron Development for W7-X

Contact: Dr. Konstantinos Avramidis

Since the very beginning of the operation of the stellarator Wendelstein 7-X (W7-X), the Electron Cyclotron Resonance Heating (ECRH) system, consisting of ten 1 MW, 140 GHz gyrotrons, has exhibited a remarkable performance. The available EC heating and current drive power in the plasma ranges from 7 to 9 MW, that is, W7-X is using the world's largest ECRH system today. The possibility of even higher ECRH power in the future is under consideration. Motivated by this, studies towards an upgraded 1.5 MW, 140 GHz gyrotron design were initiated, which showed that the most promising development path, with respect to risk and cost, would be the upgrade of the existing $TE_{28,8}$-mode gyrotron of W7-X, in order to operate in the $TE_{28,10}$ mode.

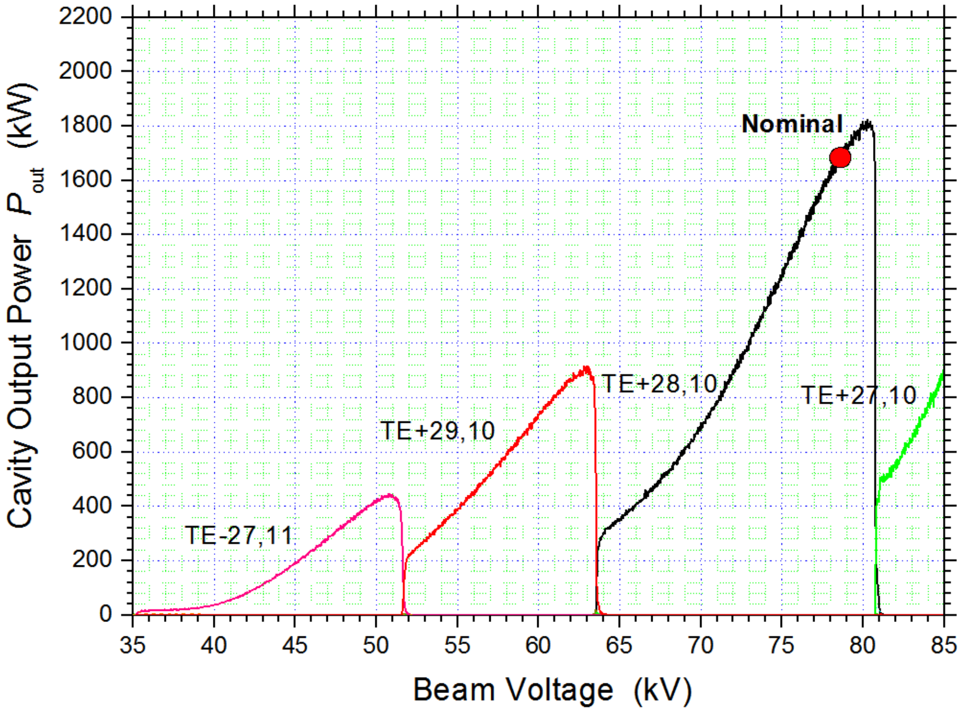

Fig. 1.1.1: Simulation of the TE28,10-mode gyrotron start-up considering 83 competing modes.

In this period, an optimised design for the cavity and non-linear uptaper of the $TE_{28,10}$-mode gyrotron has been obtained, which fulfils the specifications and requires the smallest changes with respect to the existing gyrotron layout. Beam-wave interaction simulations, taking into account realistic spreads in the electron beam parameters, verified the cavity & uptaper performance. An example is given in Fig. 1.1.1, where the $TE_{28,10}$ mode generates 1.7 MW in the cavity at nominal operation (78.5 kV, 56 A, 5.55 T) with an estimated total efficiency of 35 % without depressed collector. A first assessment of the necessary modifications of the rest of the gyrotron components has also been made.

In support to the investigations on the W7-X gyrotron upgrade, the components of a $TE_{28,10}$ mode generator for low-power tests of the quasi-optical mode converter system of the gyrotron have been designed and manufactured (Fig. 1.1.2). The mode generator has been assembled and experimental results are expected in 2018.

Fig. 1.1.2: Components for the $TE_{28,10}$ mode generator: cavity with coaxial insert (left) and taper (right).

The possibility of MW-class operation of the upgraded gyrotron at the additional frequency of 175 GHz for Collective Thomson Scattering diagnostics has been also studied. Initial results showed that the designed cavity could operate in the $TE_{36,12}$ mode and yield 1.2 MW at 175.8 GHz at the operating point of 78 kV, 55 A, 7.0 T with 26 % total efficiency without depressed collector.

1.2 Gyrotron Development for ITER

Contact: Dr. Tomasz Rzesnicki

1.2.1 Experimental study on further performance optimization of the European 1 MW, 170 GHz hollow-cavity gyrotron prototype.

The EU 1 MW, 170 GHz gyrotron with hollow cylindrical cavity has been designed within the European GYrotron Consortium (EGYC) in collaboration with the industrial partner Thales Electron Devices (TED) and under the coordination of Fusion for Energy (F4E). The experimental verification of the Short-Pulse (SP) gyrotron prototype was successfully completed in 2015. In order to investigate the further optimization of the gyrotron performance, additional tests with the modified SP prototype have started. The activities are focused on the increasing of the total efficiency towards 50 % (ITER requirement) in depressed collector operation. The saturation of the gyrotron efficiency at higher retarding voltages, which was observed during the experiments with the CW tube was theoretically predicted by simulations of the overall gyrotron geometry and is related to the reflection of electrons in the region of the mirror-box, due to a significant drop of the electron kinetic energy caused by the voltage depression of the spent beam space-charge, which defines the limits of the applicable maximum body voltage, before reflection of electrons begins. That effect is mainly governed by the geometrical arrangement of the gyrotron inside the mirror box. In order to perform a study of this effect different configuration setups, based on additional structures i.e. metallic pipes or optimized potential elevating structure (Fig. 1.2.1) installed inside the mirrorbox, have been prepared for the tests. The achieved results have been compared with an optimal depression voltage arrangement where the retarding voltage was set on the gyrotron by using of the ceramic-isolated collector of the 2 MW, 170 GHz coaxial-cavity short-pulse gyrotron prototype that is available at KIT.

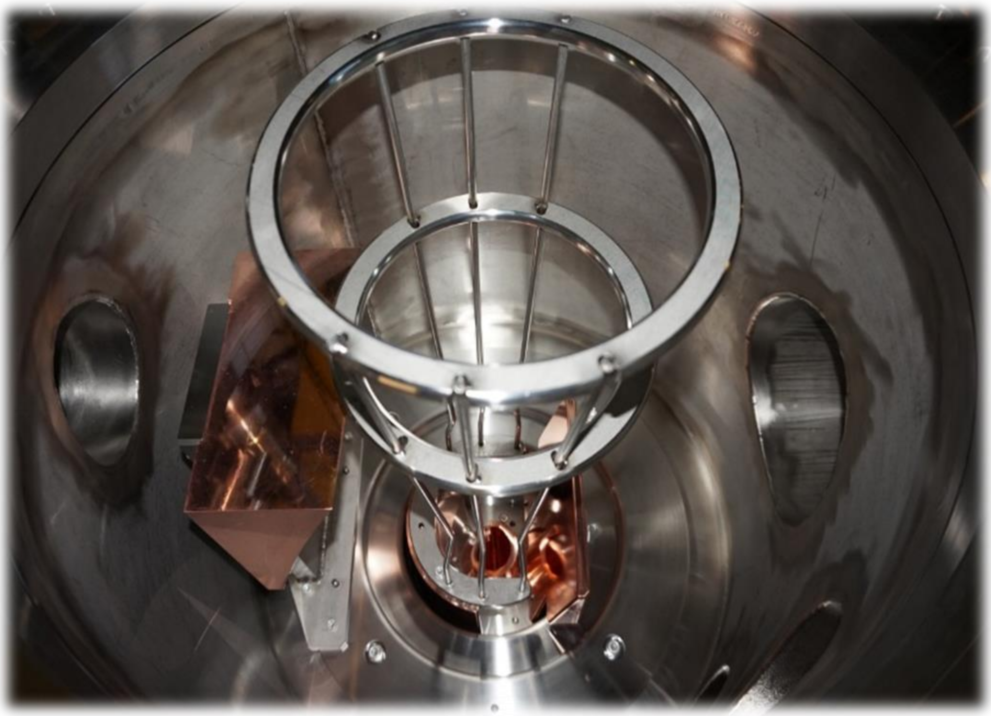

Fig. 1.2.1: Potential elevating structure.

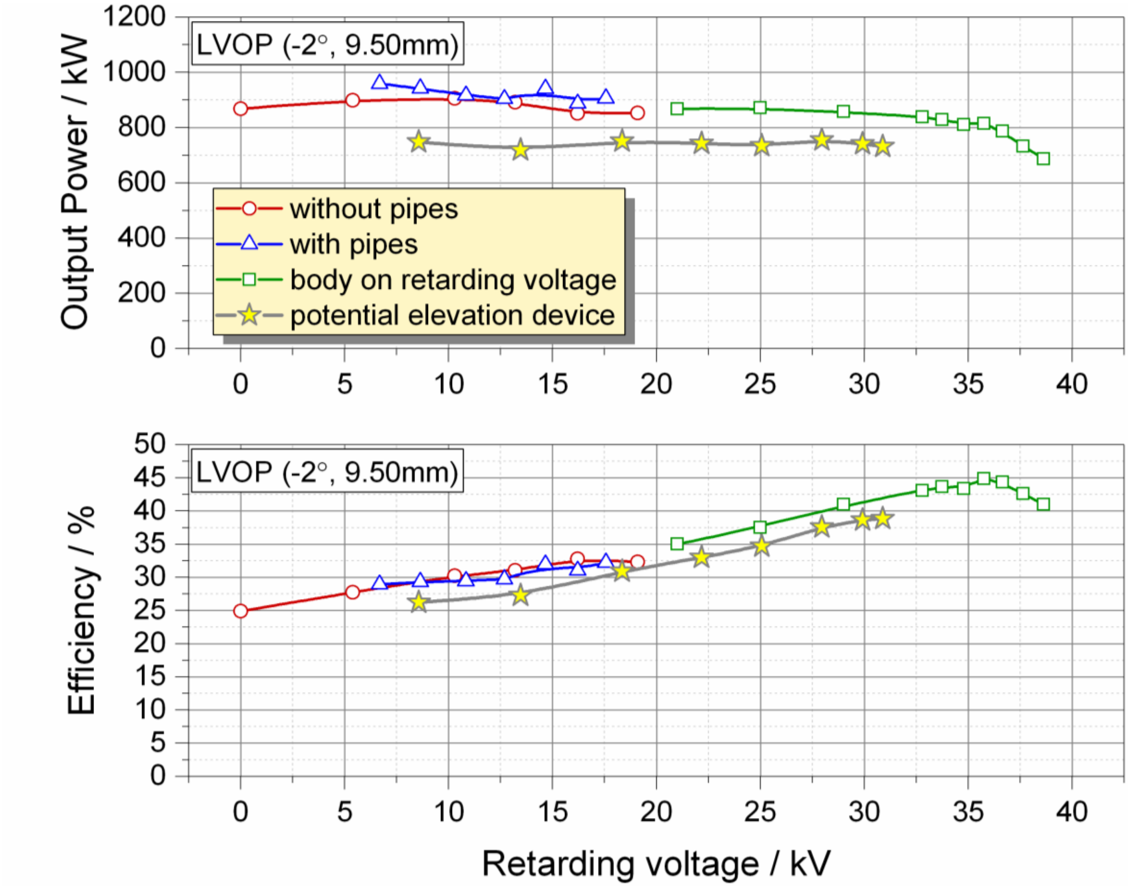

Fig. 1.2.2: RF power and total efficiency vs. retarding voltage obtained experimentally with different gyrotron configurations. *(bottom).*

Fig. 1.2.2 presents the generated RF power and the corresponding efficiency for the four different gyrotron configurations: (a) original "basic" setup in 2015 (red line), (b) cooling pipes mock-up installed in the mirror box and set on High Voltage (HV) (blue line), (c) optimized potential elevating structure (grey line) and (d) complete mirror-box set on HV (green line). In all cases the operating parameters are close to the nominal ones. As already predicted theoretically, the best results have been achieved by placing of the retarding potential on the gyrotron body. It resulted in an increase of the total gyrotron efficiency from 34 % to close to 45 % (retarding potential on the body).

Preliminary tests of the first version of the potential elevating structure confirmed a significant increase of the efficiency close to 40 %, limited by the maximal possible value of the applicable body voltage (~32 kV), due to vacuum issues. The gyrotron performance equipped with the potential elevating structure is expected to be similar to the configuration with the HV on the gyrotron body, being possibly a reasonable alternative solution for hollow cavity gyrotrons in the future. Final validation of the structure at better gyrotron conditions are planned for 2018.

1.3 Gyrotron Developments for future DEMO

1.3.1 Developments in frame of EUROfusion

Contact: Dr. Konstantinos Avramidis

The R&D towards a gyrotron that will meet the requirements posed by the envisaged Electron Cyclotron Heating and Current Drive system for DEMO is, at the largest part, performed within the Work Package Heating and Current Drive (WPHCD) of EUROfusion. The studies are in line with the European Fusion Roadmap towards a demonstration power plant. Gyrotron R&D is a necessary step to bridge the gap between today's state-of-the-art gyrotrons and future gyrotrons for DEMO. The EU DEMO1 baseline 2015 poses significant challenges on the gyrotron. These are the need for dual, high-frequency operation (170/204 GHz) and/or fast frequency step-tunability, as well as the requirements for higher power (2 MW), higher overall efficiency (≥60 %), and a higher level of Reliability-Availability-Maintainability-Inspectability (RAMI) in line with that of a power plant. To keep the gyrotron R&D relevant with respect to possible baseline changes and to alternative reactor configurations towards a future power plant, efficient MW-class gyrotron operation at higher (~240 GHz) frequencies is also considered in parallel.

The advanced concept of the coaxial gyrotron has been selected as being the most promising, compared to the conventional hollow-cavity gyrotron, towards the higher power and frequency target, since the enhanced mode selectivity of coaxial cavities permits stable operation at very high-order modes, which are compatible with large dimensions of the gyrotron cavity. The 170 GHz, 2 MW short-pulse coaxial gyrotron at KIT has already exhibited excellent performance at ms pulses. The next step for coaxial gyrotron technology towards DEMO is to prove experimentally its capability for long-pulse operation, especially with respect to the cooling and alignment of the coaxial insert. To this end, the coaxial gyrotron has been upgraded in this period with new, water-cooled components and experiments targeting at 100 ms pulses are expected in early 2018. The gyrotron is shown in Fig. 1.3.1. Supportive multi-physics numerical investigations on the cooling of the coaxial insert have also been performed. It was predicted that the cooling is compatible with continuous-wave operation. According to the calculations, a heat flux to the insert of up to 0.39 kW/cm2 and an insert misalignment of up to 0.2 mm can be acceptable. This gives a large margin with respect to the expected values (i.e. heat flux < 0.15 kW/cm2, misalignment < 0.1 mm).

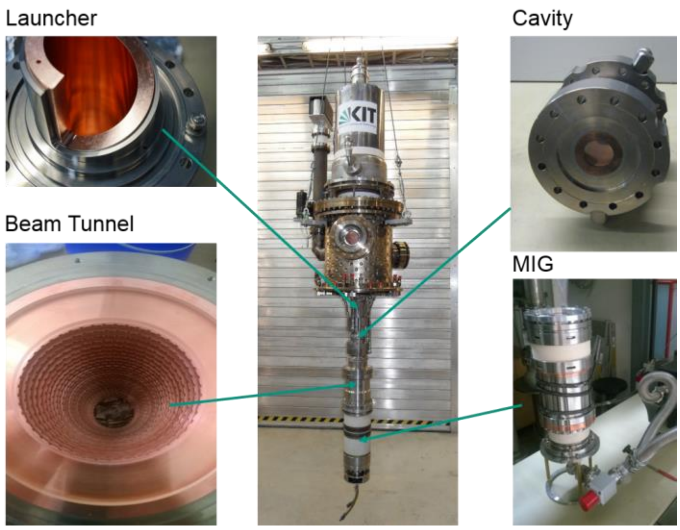

Fig. 1.3.1: The assembled longer-pulse 2 MW coaxial gyrotron and its components.

To keep the development path towards the DEMO gyrotron as fast and cost-effective as possible, the design of a 2 MW, 170/204 GHz coaxial gyrotron has been initiated using the existing 170 GHz, 2 MW coaxial gyrotron as a starting point. A preliminary assessment showed that a good performance can already be achieved with relatively minor modifications of the existing gyrotron. MW-class operation at 237 GHz seems also possible. The investigations focused on the gyrotron cavity and its calculated performance is summarised in Table 1.3.1. The Table includes results for the existing cavity of the coaxial gyrotron as well as for a proposed, slightly modified coaxial cavity with a shorter midsection, which achieves a more balanced performance at the three different frequencies. In parallel, the theoretical studies on 2 MW, ~240 GHz gyrotrons operating at very-high-order modes have been continued, focusing on the tolerance of misalignments and on start-up scenarios using triode-type electron guns to increase the mode selectivity.

Cavity	Existing coaxial cavity			Modified coaxial cavity		
Frequency [GHz]	170.00	204.14	237.17	170.04	204.16	237.18
Operating mode	$TE_{34,19}$	$TE_{40,23}$	$TE_{48,26}$	$TE_{34,19}$	$TE_{40,23}$	$TE_{48,26}$
Beam energy [keV]	90	80.7	60	92.8	88	78
Beam current [A]	75	70	60	75	75	70
Cavity power [MW]	2.25	1.8	1.04	2.5	2.2	1.63
Interaction efficiency [%]	34.9	33.0	30.2	36.7	33.4	30.2

Table 1.3.1: Simulated performance of triple-frequency operation of the coaxial gyrotron cavity.

The target of ≥ 60 % efficiency for the DEMO gyrotron implies the development of advanced, Multi-Stage Depressed Collectors (MDC) to increase the energy recuperation from the spent electron beam. Given that in the gyrotron the electrons are guided by a strong magnetic field to the collector, the required separation of electrons according to their energy, necessary for MDC operation, is quite challenging. Extensive investigations on different MDC concepts culminated in a very promising configuration, based on the E×B drift concept and adopting helical electrodes (Fig. 1.3.2). Extensive Particle-In-Cell simulations of a two-stage collector showed very good handling of secondary electrons, which is one of the major issues in MDCs, and demonstrated a collector efficiency of 77 %, resulting in an overall gyrotron efficiency of 63 %. Excellent tolerance in electron beam misalignments and stray magnetic fields was also demonstrated. The latter is shown in Fig. 1.3.2.

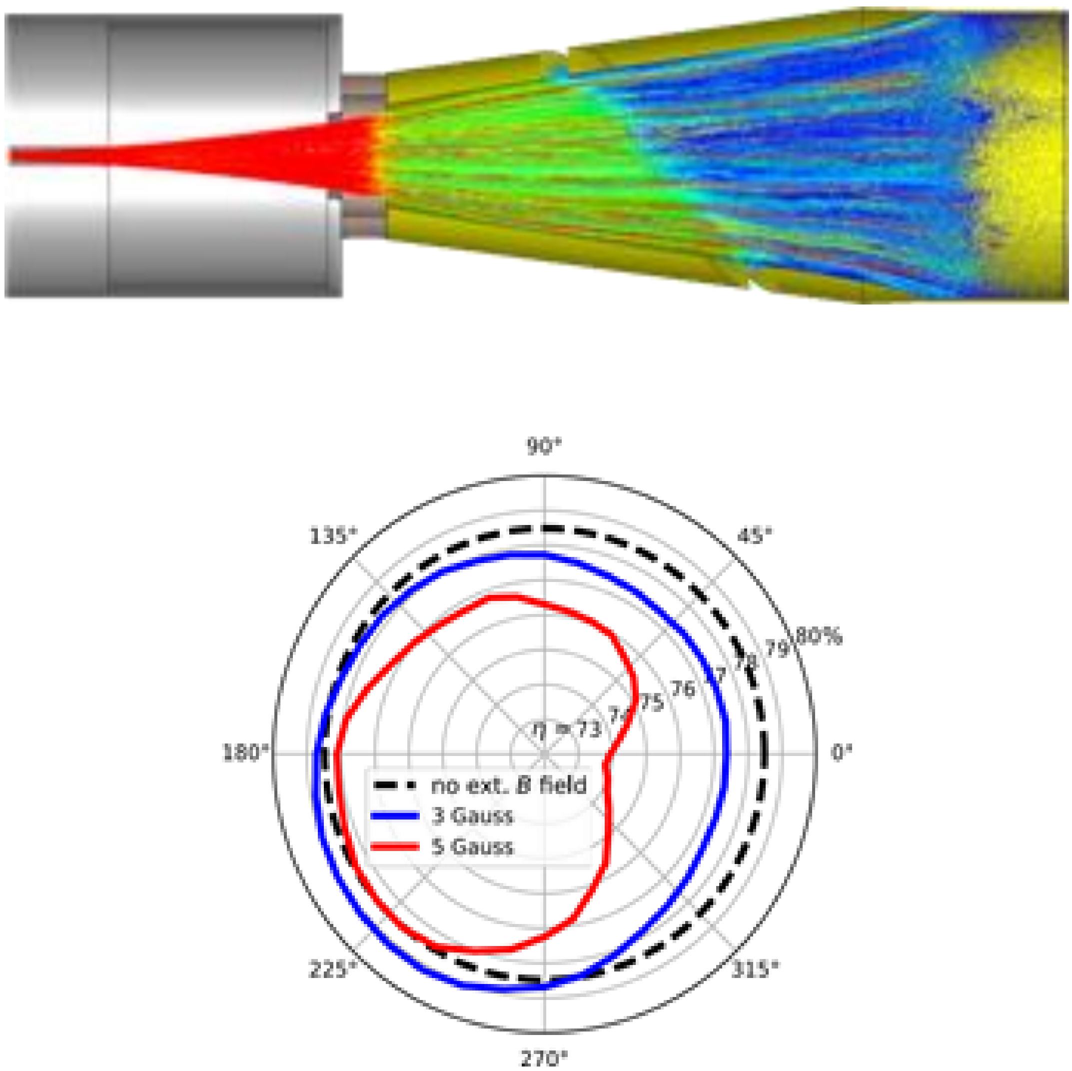

Fig. 1.3.2: Top: a two-stage E×B helical MDC with electron trajectories colour-coded according to kinetic energy. Bottom: dependence of the collector efficiency η on the direction of a perturbing magnetic field perpendicular to the collector axis.

The required high RAMI level of a DEMO gyrotron calls for further optimisation of all critical gyrotron components in terms of reliability and robustness. In this frame, investigations on advanced cooling methods of the gyrotron cavity, including micro-channel cooling and spray cooling have been initiated. More important, a new advanced triode-type Magnetron Injection Gun (MIG) has been procured for the existing coaxial gyrotron by Thales Electron Devices (TED, Vélizy-Villacoublay, France) and will be installed in the gyrotron in 2018. The gun is designed to be free of electron trapping mechanisms, i.e. compatible with long-pulse operation and is manufactured with coated emitter edges to minimise the influence of manufacturing tolerances and edge effects on the electron beam quality (Fig. 1.3.3). This is the first time in Europe that this technology is used for gyrotrons.

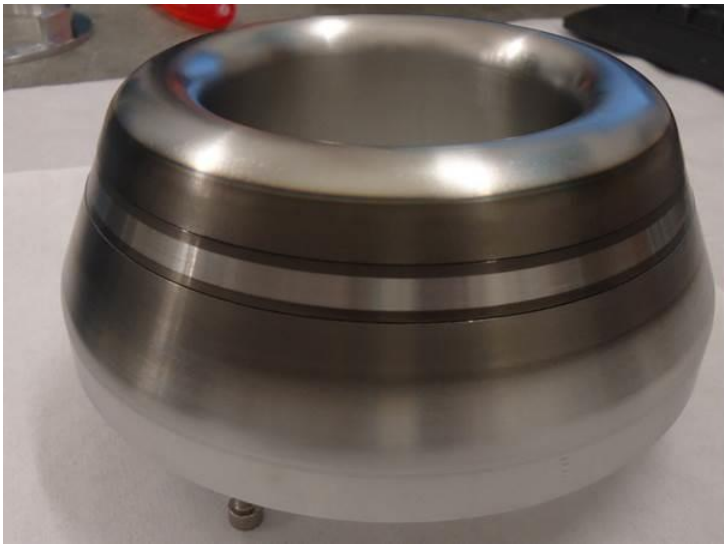

Fig. 1.3.3: MIG mock-up cathode with coated emitter edges.

1.3.2 2 MW, 170 GHz longer pulse coaxial-cavity gyrotron prototype.

Contact: Dr. Tomasz Rzesnicki

For fusion power plants that shall generate significant electric power such as DEMO the required RF power, efficiency, and operating frequency of gyrotrons needs to be further improved. A minimum RF output power of 2 MW at continuous wave (CW) and at operating frequencies up to 240 GHz are currently required. In order to satisfy those requirements, KIT is working on advanced gyrotron concepts, particularly on the coaxial-cavity gyrotron technology. Experiments at KIT demonstrated its superior performance by showing an RF output power above 2.2 MW in short pulses (ms-range) at an operating frequency of 170 GHz. In comparison to the classic hollow-cavity gyrotron technology widely used in todays fusion gyrotrons the coaxial-cavity gyrotron technology offers reduced voltage depression and mode competition. That allows an operation at very high-order operating modes, which leads to a significant higher RF output power. At KIT a modular-type of 2 MW 170 GHz coaxial-cavity short-pulse (ms) pre-prototype gyrotron operating at very short pulses up to a few milliseconds has been used to verify the superior performance of the coaxial-cavity gyrotron technology so far. A first industrial 170 GHz 2 MW coaxial-cavity gyrotron prototype operating at long pulses was built and was tested for ITER in 2012. In favor of the ITER EU 1 MW gyrotron development that 2 MW development was put on hold for ITER. Nevertheless, in frame of EUROfusion and supported by F4E the coaxial-cavity development continues at KIT. Currently, the main focus of KIT is to verify the performance of the coaxial-cavity gyrotron at longer pulses. As a first step towards a coaxial-cavity gyrotron operating at CW, a new modular gyrotron prototype was constructed, with the goal to extend the pulse lengths up to 1 s. This tube allows the verification of the gyrotron performance at extended pulse duration and validation of all operating parameters relevant for further CW operation. Furthermore, the pre-validation of the critical gyrotron components at longer-pulse regime is possible, in particular the behavior of the inner conductor, during heating up. Hence, the main issue for the construction of the new propotype gyrotron was the introduction of a reliable cooling systems for the beam tunnel, cavity, launcher, quasi optical mirror system, CVD diamond output window and the collector. Due to the presence of an independent cooling system for each component, monitoring of the internal losses in each gyrotron component and of the final energy balance of the tube during longer-pulse operation is possible. A very big advantage of this longer-pulse gyrotron is the modular construction. It allows an easy implementation and testing of new subcomponents with advanced water cooling systems, material compositions and geometries. The assembled longer-pulse gyrotron, installed in the superconducting (SC) magnet, ready for the first operation is shown in Fig. 1.3.4.

A bake-out procedure of the complete tube has been applied resulting in significantly better vacuum conditions. Experimental results will be expected in 2018.

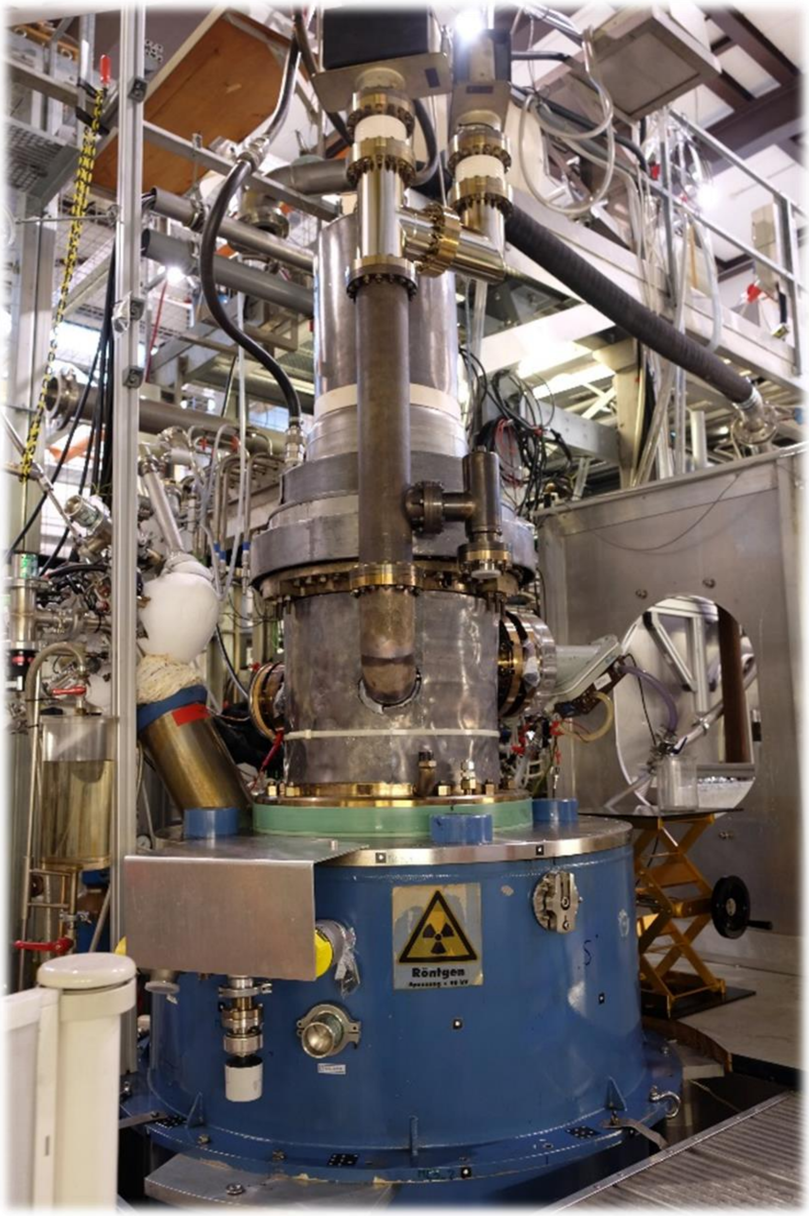

Fig. 1.3.4: The KIT 2 MW coaxial-cavity longer pulse gyrotron in the superconducting magnet.

1.4 Developments on theory and numerical simulations

Contact: Dr. Stefan Illy

1.4.1 Cavity simulation and beam-wave interaction tools

A multi-physics numerical procedure has been established, in collaboration with the Polytechnic University of Turin, which models the influence of the thermal expansion of the gyrotron cavity on the expected gyrotron performance. It is an iterative simulation method, which involves electrodynamic, thermal-hydraulic, and thermo-mechanical simulations. For the electrodynamic simulations, the in-house code-package EURIDICE for gyrotron interaction calculations and cavity design is used. A new module for addressing different models for the temperature dependence of the cavity wall conductivity has been developed and included in EURIDICE. Four different models were implemented, based on the ITER Material Properties Handbook as well as other sources. The materials under consideration are Glidcop and pure copper, which are the ones used in gyrotron cavities. The multi-physics numerical procedure has been used to simulate the European 170 GHz, 1 MW continuous-wave prototype gyrotron for ITER, considering both the existing cavity cooling system (see Fig. 1.4.1) and proposals for an improved cooling system. The longer-pulse 170 GHz, 2 MW coaxial gyrotron at KIT was also simulated using this procedure.

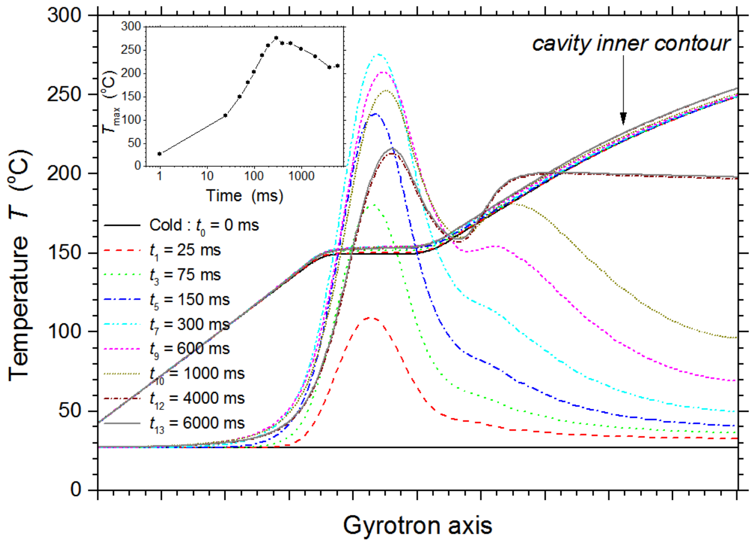

Fig. 1.4.1: Temperature profile along the inner contour of the cavity of the EU gyrotron for ITER, as obtained by transient multi-physics modelling. The change of the inner contour due to the thermal expansion is also shown. The inset shows the evolution of the maximum temperature with time.

Advances in the modeling of the beam-wave interaction in gyrotrons using 3D, full-wave, Particle-In-Cell (PIC) codes have been made. Technical details, theoretical input, and numerical results from the in-house code-package EURIDICE have been provided to support PIC simulations of test cases as well as real gyrotrons using CST Particle Studio, the code PICLas from the University of Stuttgart, and VORPAL. In all simulated cases a good agreement between the codes has been reached. This has been a significant step in increasing the confidence in 3D, full-wave PIC codes with respect to their capability of reliable simulations of the gyrotron interaction.

1.4.2 Improvements of the electron beam-optics codes

ESRAY

The beam-optics toolbox ESRAY has been extended to allow a smoother simulation of the so-called vertical sweeping of gyrotron collectors. In this case strong eddy currents are induced in the relatively thick cylindrical copper wall of the collector. Since the magnetic field calculation tool of ESRAY can not handle eddy currents, this part of the simulation has been shifted to the freely available FEMM simulation program. ESRAY has been extended to allow better interaction with FEMM with regard to the definition of coil geometries, materials and data exchange between both programs. This now allows the definition of arbitrary waveforms for the sweeping current based on a Fourier series expansion of the current and the corresponding periodic magnetic field distribution in the collector. In the frame of a Bachelor thesis from Jackowski (2017), a conceptual study has been performed to show the possibility and benefits of vertical sweeping with advanced, optimized sweeping current waveforms. Fig. 1.4.2 illustrates the shape of such a waveform applied to a proposed coil for the relatively compact collector of the 2 MW, 170 GHz coaxial cavity "longer pulse" gyrotron. Fig. 1.4.3 shows the corresponding load profile on the collector wall, indicating that the critical peaks of the wall loading will be reduced by nearly a factor of two compared to conventional sweeping with a sinusoidal waveform.

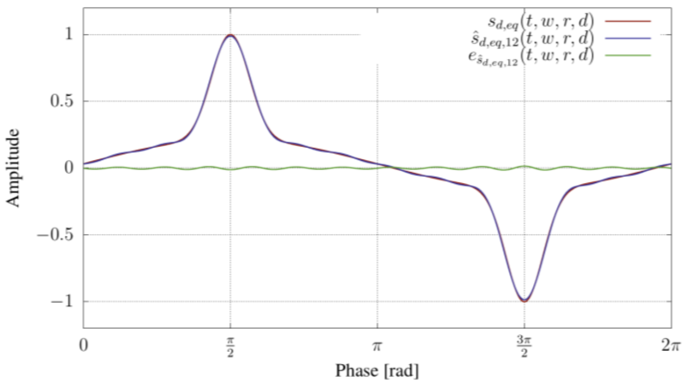

Fig. 1.4.2: Proposed current waveform for the enhanced sweeping concept, indicating the shape of the pre-defined current, it's approximation by a Fourier series and the (negligible) corresponding difference *e*.

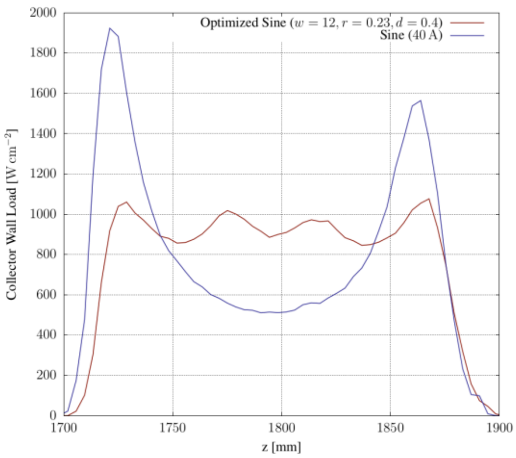

Fig. 1.4.3: Obtained averaged power density for the case of sinusoidal sweeping (blue) and sweeping with the advanced current waveform (red).

ARIADNE

The tracking code ARIADNE has been extended to allow convergence at the presence of trapped electrons. This is achieved by the definition of two relaxation factors: (i) the first one for the electron beam space charge required for the Poisson solver, and (ii) the second one for the definition of the amplitude of the mode in the cavity. In particular, for the solution of Poisson equation not only the space charge of the beam at the last iteration is considered, but also the space charge of the previous iteration. The percentage of the space charge contribution of the previous iteration and the last one is defined by a user defined variable. Similar procedure is followed with the amplitude of the mode in the cavity. The amplitude of the mode in the cavity is defined by the energy losses of the beam electrons at the last iteration, but also the energy losses of the previous iteration. Similar to the space charge contribution, a user defined factor determines the percentage of the last and the previous iteration contributions on the cavity mode amplitude. Using this upgrade, it was possible to numerically investigate the behavior of the beam electrons in case of applying a high deceleration voltage at the collector which causes electron reflections. It was possible to estimate the reflected current and the drop of the generated power as a function of the decelerating voltage and to investigate the peculiar trajectories of the reflected electrons.

In addition, the distributed memory parallization scheme of ARIADNE has been upgraded to a hybrid scheme in order to get the advantages of the multi-core share memory nodes of modern clusters. In particular, the distributed memory parallelization scheme based on MPI was upgraded with an additional shared memory scheme based on OpenMP. The whole mesh is stored only once in each node of the cluster, while the calculation of the electron trajectories are distributed on all processes (cores) of the nodes. In this way, it is avoided the multiple storage of the mesh in the memory of the same node and provide us the possibility to significantly increase the mesh density and the number of electrons considered in simulations.

1.4.3 Simulation and design of quasi-optical components

TWLDO (Tools for Waveguide Launcher Design and Optimization)

The method used in the TWLDO code for the analysis of the field distribution on the launcher wall has been improved. In TWLDO code, the input field of launchers is defined as the field distribution on waveguide walls in the area $-\infty < \mathrm{z} < 0$. In the numerical calculation, it is impossible to calculate the field distribution in the semi-unlimited input area ($-\infty < \mathrm{z} < 0, \mathrm{z} = 0$ means the entry of launcher), therefore the field distribution in the area $-7\mathrm{L} < \mathrm{z} < 0$ on waveguide walls is used to approximate the semi-unlimited input area, where L is the launcher length. In the case that the discontinuity point of the field distribution is far away from the launcher (at z=-7L), the influence of the discontinuity on the field distribution on the launcher wall (at z>=0) is quite small. In the modified TWLDO code, in order to depress the influence of the discontinuity, the input field f in the area $-7\mathrm{L} < \mathrm{z} < -6\mathrm{L}$ is smoothly increased from 0 to the full cavity field f_c as following:

$$\mathrm{f} = \begin{cases} \mathrm{f_c}\left(\dfrac{1-\cos\left(\dfrac{(\mathrm{z}+7\mathrm{L})\pi}{\mathrm{L}}\right)}{2}\right) & -7\mathrm{L} < \mathrm{z} < -6\mathrm{L} \\ \mathrm{f_c} & -6\mathrm{L} < \mathrm{z} < 0 \end{cases}$$

The simulation results show that the influence of the discontinuity due to the limited calculation area has been depressed by this procedure.

A quasi-optical launcher for both co- and counter-rotating mode operating in the $TE_{32,9}$ mode at 170 GHz has been designed and tested using TWLDO code. The wall profile and the field distributions on the launcher wall are shown in Fig. 1.4.4. The position of the wave beams should be well arranged so that the both wave beams from $TE_{32,9}$ mode and $TE_{-32,9}$ mode could be located at the center of the launcher aperture.

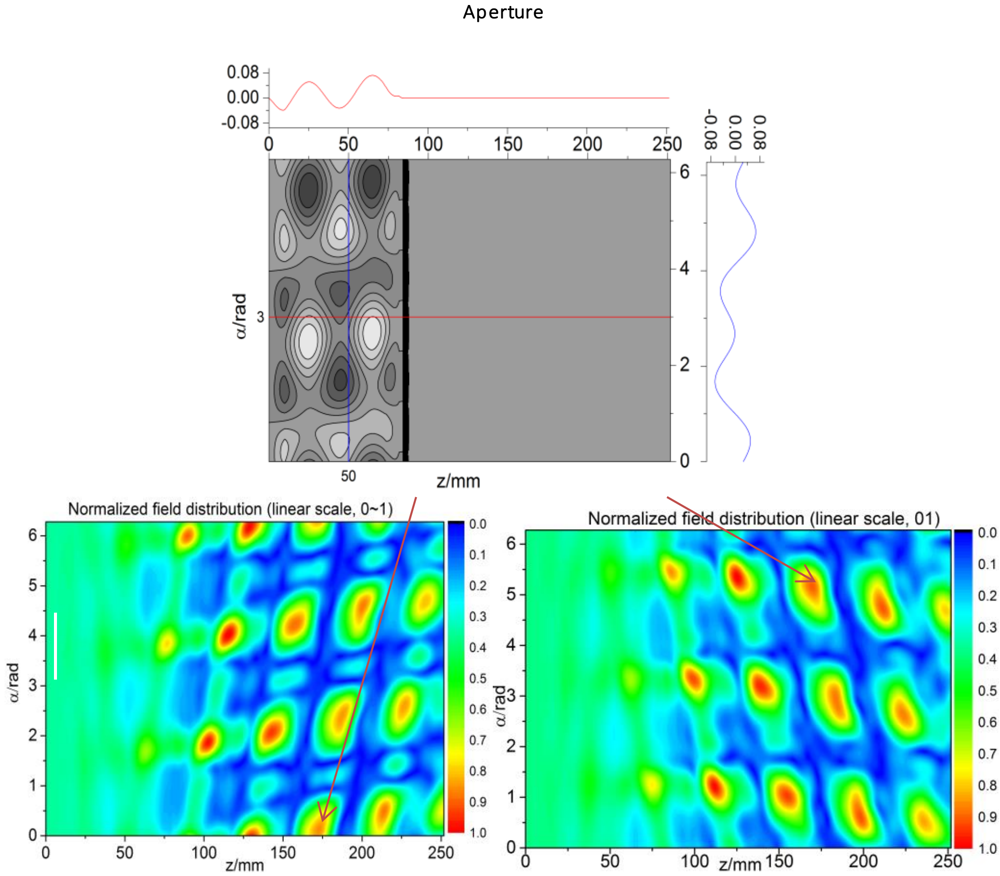

Fig. 1.4.4: The wall profile (left), the field distribution of the co-rotating mode (middle) and the counter-rotation mode (right).

KarLESSS (Karlsruhe Large Electric System Simulation Suite)

An advanced computer code (KarLESSS) [Ma17] for the full-wave simulation of quasi-optical systems in high-power gyrotrons is under development. The simulation program solves the electric-field integral equation with the method of moments. For an acceleration of the simulations, advanced methods as high order basis functions, high order meshes and compression algorithms based on the adaptive cross approximation (ACA) are used. In 2017, optimized versions of the ACA were implemented (ACA-SVD and SPACA). The so called ACA-SVD algorithm combines the ACA with an additional singular-value-compression to reduce the required memory during a simulation. The SPACA introduces a sub-sampling and a tree-structure of the basis functions to reduce the required calculation time and memory of the normal ACA. With the SPACA the favorable scaling of N*log(N) could be reached for the simulation of quasi-optical systems. In addition, an own preconditioner-algorithm, specialized for the ACA and its optimized versions was developed. With the developed preconditioner the convergence of the FGMRES algorithm, used for the solution of the system of linear equations, is effectively reduced.

1.5 FULGOR (Fusion Long-Pulse Gyrotron Laboratory)

Contact: Dr. Gerd Gantenbein

The existing gyrotron test facility at KIT, which had been designed and built more than 30 years ago, plays a worldwide leading role in the development of high-power gyrotrons for nuclear fusion applications. This facility offered the unique opportunity to develop and test the first CW high power series gyrotrons for the stellarator W7-X in collaboration with IPP and Thales Electron Devices as the industrial partner.

The target parameters of the new gyrotron test facility are well beyond the capabilities of the existing one. The new teststand will strongly support KIT's leading role in the development of advanced gyrotrons. It will help to answer the questions regarding the technical limits and new physical designs for future high-power microwave tubes. The key parameters of FULGOR will be:

- Full CW operation with up to 10 MW electrical power (corresponding to >= 4 MW RF power, assuming an efficiency of the gyrotron >= 40%)
- Support of advanced energy recovery concepts, e.g. multi-stage depressed collector (MSDC)
- Super conducting magnet with a flux density of up to 10.5 T

The high voltage power supply (HVPS) will support an operating voltage of up to 130 kV with up to 120 A beam current in short pulse operation and 90 kV / 120 A in continues wave regime. The superconducting magnet will allow operation of gyrotrons at frequencies well above 200 GHz (~ 240 GHz). Other significant components of the teststand are: cooling system, control electronics and interlock system, RF diagnostics including high-power RF absorber loads.

The capabilities of FULGOR will enable the development and CW tests of gyrotrons for future fusion machines like ITER and DEMO. Fig. 1.5.1 shows a simplified CAD view of the complete FULGOR system.

Substantial progress has been achieved in the planning, procurement and installation of major systems of the new teststand.

High Voltage Power Supply (HVPS): All EPSM power modules for CW operation (84 in total) have been tested (at AMPEGON), delivered and installed at KIT side. First tests of this system show very good results in agreement with the specifications. All modules of the pulsed power supply (PPS) (40 in total) for up to 5 ms operation have been produced, delivered and installed. A first phase of commissioning has been completed end of 2017, final acceptance will be in Q2/2018. Discussions with industry on a body power supply, necessary for operation of the gyrotron with energy recovery of the spent electron beam, have been started. The specifications have been fixed and several offers have been evaluated. The start of the procurement is expected for early 2018.

Cooling system: The cooling system is designed for full 10 MW CW operation. The final acceptance of the complete cooling system has been performed in 2017.

Control and data acquisition: The procurement and installation of components to control the teststand (HV power supply, cooling system, gyrotron control and diagnostic) has been continued.

Superconducting magnet: In 2017 the specifications of the magnet has been finalized, a call for tender has been launched and the system has been ordered. The key data of the magnet are: borehole diameter: 261

mm, max. B-field: 10.5 T, dipole coil system to optimize the electron beam position in the gyrotron, cryogen-free. The delivery of the system is scheduled for mid of 2019.

Microwave diagnostics: In cooperation with IGVP, University Stuttgart, the transmission system for the RF beam from the gyrotron window to the absorber load has been discussed. This system will include two matching mirrors and two polarisers which will allow broadband transmission. At IGVP the water cooled matching mirrors and a 2 MW absorber load have been ordered. The polarisers will be manufactured at KIT.

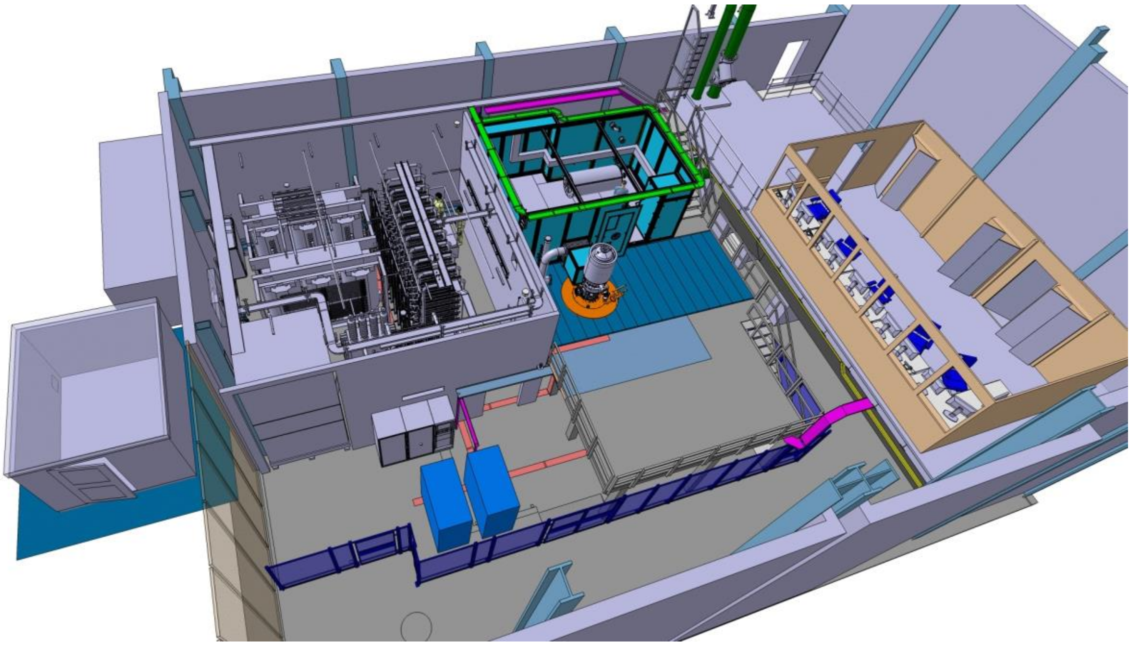

Fig. 1.5.1: FULGOR

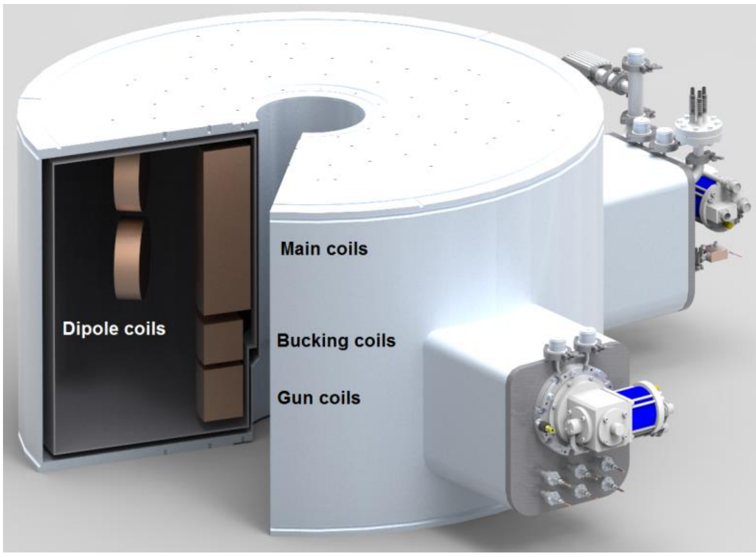

Fig. 1.5.2: NN: 10.5 T magnet with integrated dipole coils (Tesla Engineering Ltd).

1.6 Generation of ultrashort pulses using advanced gyro-TWT design

Contact: M.Sc. Alexander Marek

We study the generation of a periodic sequence of powerful short pulses in this project. The need for powerful pulsed sources of millimeter and sub-millimeter (sub-THz) radiation is motivated by a large number of fundamental problems and practical applications, including diagnostics of plasma, photochemistry, biophysics, new locating systems, and the spectroscopy of various media.

The pulses will be formed by a feedback loop of an amplifier and a nonlinear absorber (see Fig. 1.6.1). Both, amplifier and absorber will be realized as gyrotron-traveling-wave-tubes with helical corrugated interaction-region. The amplifier will run in a regime optimal for the maximal amplification of ultrashort pulses, while the absorber will run in the so called Kompfner dip regime, where low-energy pulses are absorbed while powerful pulses can pass the absorber without loss of energy.

For prove of concept, such a feedback loop should be first realized at a frequency of 35 GHz, but the final applications of the generated pulses will be in the sub-THz frequency range. Therefore, the key elements for a helically corrugated gyro-TWT with the frequency of 260 GHz, as well as a non-linear cyclotron absorber appropriate for this frequency range will be developed in parallel to the design of a feedback-loop at 35 GHz.

“Cold” simulations of the helical interaction region and of additional components as mirror systems for input/output systems were performed in a first step of the project [Ma17]. For this, our in-house developed full-wave simulation tool KarLESSS was used. Currently, “hot” simulations of the interaction are performed. Simulations of the separated amplifier and absorber components at 35 GHz are performed with the commercial tool CST [Gi17]. In parallel, we investigate in the usage of the advanced simulation program “PICLas”, developed by the Institute of Aerodynamics and Gas Dynamics at the University of Stuttgart. PICLas provides the great opportunity to verify the CST simulations and to allow a full PIC simulation of a coupled amplifier-absorber system.

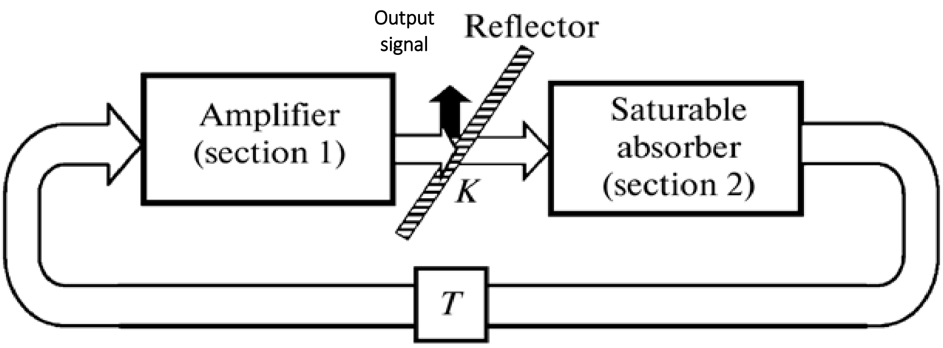

Fig. 1.6.1: Schematical view of concept, K: adjustable reflection factor, T: delay time of feedback coupling.

Collaboration: In Collaboration with the Institute of Applied Physics, Russian Academy of Sciences (IAP- RAS) and with support of the Institute of Aerodynamics and Gas Dynamics, University of Stuttgart.

Funding: The research is supported by the joint RSF-DFG project (Je 711/1-1) Generation of Ultrashort Pulses in Millimeter and Submillimeter Bands for Spectroscopy and Diagnostic of Various Media Based on Passive Mode-locking in Electronic Devices with Nonlinear Cyclotron Absorber in the Feedback Loop.

Involved Staff:

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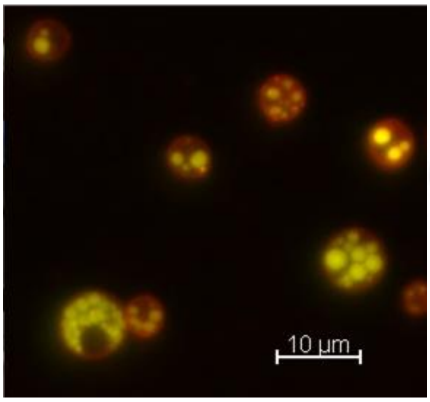
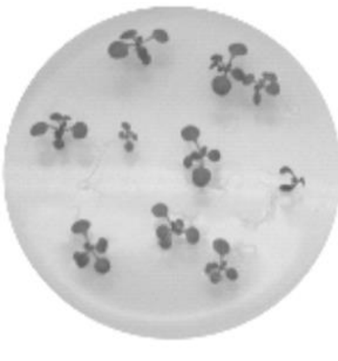
2 Renewable Energy (RE): Bioenergy -Feedstocks and Pretreatment-

Contact: Prof. Dr. Georg Müller

The Department for Pulsed Power Technology is focusing on research and development of pulsed power technologies and related applications. The applications involves the electroporation of biological cells for extraction of cell contents (PEF- process), dewatering and drying of green biomass, pre-treatment of micro algae for energetic use and sustainable reduction of bacteria in contaminated effluents. Another key research topic is devoted to the development of corrosion barriers and materials for improved compatibility of structural materials in contact with liquid metal coolants. This year's report focuses primarily on the activities and results of ongoing third-party funded projects of the department.





PEF treatment, 10ns pulses

2.1 Microalgae cultivation and processing

Contact: Dr. Wolfgang Frey

Pulsed electric field treatment maintains cell shape, does not produce cell fragments and consequently allows real cascade processing of microalgae biomass for implementing a zero-waste biorefinery. During the past period, subsequent processes for recovery and valorization of the water-soluble fraction, the protein fraction and the lipids have been further developed. Finally, utilization of the residual biomass for biogas production have been assessed. Furthermore, new activities were started on bacterial decontamination of industrial water streams and on stress-responses of Spirulina microalgae biomass.

2.1.1 PEF4AlgBiotics

Contact: Dr. Christian Gusbeth

Title of the bilateral project, between IHM-KIT and University of Belgrade (UB) is: *Integrated Pulsed Electric Field Extraction and Lactic Acid Bacteria Fermentation for the Production of Microalgal Extracts Fortified with Probiotics* (PEF4AlgBiotics). The objective of this project is to develop a utilization option for the water-soluble fraction which spontaneously is released after PEF-treatment of microalgae. It targeted on the production of higher-value components from aqueous microalgae fractions by lactic acid fermentation (LAF) by probiotic bacteria which were grown in the aqueous fraction separated after PEF-treatment. The UB team was responsible for growth optimization of lactic acid bacteria (LAB) exhibiting probiotic characteristics and for evaluation of the effect of LAF on antioxidant properties of the fermented suspension.

Two microalgae strains, *Chlorella vulgaris* and *Auxenochlorella protothecoides*, have been selected to meet the requirements, such as having sufficient antioxidant activity and providing a growing substrate for LAB. The impact of the PEF treatment on chemical composition of the water-soluble fraction has been elaborated. Investigations were performed with the microalgae *C. vulgaris* and *A. protothecoides*, which are able to accumulate large amounts of lipids (up to 70% of the dry biomass) as energy storage molecules. We have found that a lipid-to-protein ratio of 1: 1 is optimal for extracting proteins by PEF treatment. While in case of *C. vulgaris* up to 50% of the protein content could be recovered, we were able to extract less than 10% from *A. protothecoides*. Hence, for further investigation we used *C. vulgaris* as model organism. The LAF performed on the water-soluble fraction, which was recovered within 2 h after PEF treatment, satisfied the growth requirements of LAB and had an increased antioxidant activity of the suspension after fermentation.

Funding: DAAD PPP Serbia 2017

2.1.2 Protein Extraction: Bioeconomy Graduate Program "BBW ForWerts"

Contact: Daniel Scherer Collaboration

Pulsed electric field (PEF)-assisted protein extraction from microalgae biomass: With regard to a rising demand for protein sources, microalgae are currently being discussed as an alternative source of protein for food and feed applications.

In order to extract proteins, it is usually necessary to disrupt the cells by mechanical force such as high-pressure homogenization (HPH), bead-milling or sonication. These methods all create cell debris and homogenize the biomass components, which makes separation of the debris from the extract a challenging task. An alternative to these mechanical disruption methods is the PEF-treatment that permeabilizes the cell membrane by electric field application. The extraction yield is lower compared to the aforementioned mechanical methods, but the idea is to extract the proteins through the permeabilized membrane without creating cell debris and thus maintaining separability of other biomass compounds. This makes it possible to embed PEF-treatment into a processing cascade in which the microalgae biomass can be fractionated and sequentially extracted for proteins and lipids. Then, the residual biomass can be used for energy-related processes such as biogas fermentation or hydrothermal liquefaction (HTL).

In the course of this research program, we established the microalgae *Chlorella vulgaris* as our model organism to investigate PEF-applications. We also established various protocols utilizing infrared-spectroscopy and modified Lowry assay to determine protein content of our algae and extraction yields respectively. The extracted proteins were visualized using SDS-polyacrylamide gel electrophoresis (SDS-PAGE). While establishing these methods we observed striking differences in the two protein extraction processes. Unlike HPH, where proteins are immediately released into the environment, proteins are released gradually in a time-dependent manner after PEF-treatment.

In a subsequent work the factors which influence the protein release kinetics after PEF- treatment were investigated. It was found that protein release is influenced by the algae concentration, extraction time and extraction temperature and is also influenced by extreme values of pH. It was concluded that extreme temperatures and pH values are counterproductive wheras extraction under physiological conditions results in maximum yield. Our results so far indicate that PEF-treatment induces a controlled, systematic breakdown of the biomass by some intrinsic enzymatic activities. These results have also been presented at status seminars for the BBW ForWerts graduate school and microalgae subgroup meetings with collaborators of the University of Hohenheim.

Moving on from these findings we intend to investigate the characteristics of protein fractions obtained by mechanical methods such as HPH and our PEF-treatment in terms of aminoacid composition and technofunctional properties (e.g. foaming, gelling, emulgation, solubility) with our collaborators from the University of Hohenheim. With our collaborators from the IKFT we want to investigate how the residual, protein-extracted biomass can be used in the energy-related HTL process and which quality the resulting crude oil has.

Funding: Bioeconomy Graduate Program BBW ForWerts / LGF scholarship

2.1.3 Pulsed Electric Field (PEF) application for biofertilizer production from wet microalgae biomass through enzymatic hydrolysis

Contact: Dr. Sahar Akaberi

It is known from literature that microalgae can contain a high amount of proteins. The strain Scenedesmus almeriensis exhibits a comparably high content of proteins of 30-55 % of the cell dry weight. In 2012, Romero Garcia et al., has introduced a process for the production of amino acid concentrates to be utilizes as biofertilizer from S. almeriensis through enzymatic hydrolysis. Due to the presence of the rigid cell wall, a cell disruption method is necessary improve enzyme access into the cell and, in consequence to increase the hydrolysis yield of algal proteins to amino acids. In the European project SABANA, Sustainable Algae

Biorefinery for Agriculture and Aquaculture, PEF-treatment was suggested as an energy efficient cell disruption method prior to enzymatic hydrolysis.

To provide biomass for process development the new strain S. almeriensis was transferred to the IHM lab. Since mid of 2017 S. almeriensis are cultivated in shaker-culture and in 25 liter photobioreactors. The latter allows obtaining a larger volume of higher pre-concentrated biomass.

For PEF-treatment of S. almeriensis biomass, fresh S. almeriensis was harvested and concentrated by centrifugation to reach at least a biomass concentration of 50 gdw/l of suspension. Continuous-flow PEF-treatment was performed with 1 µs long pulses at an electric filed strength of 40 kV/cm and at a treatment energy of 150 kJ per liter of suspension. PEF-treated microalgae were analyzed microscopically. As expected, cell structure was preserved after PEF-treatment. Other parameters, such as conductivity changes showed the efficiency of pulse parameters.

The enzymatic hydrolysis was done by adding the commercial enzymes Alcalase 2.5 L and Falvourzyme 1000 L to the pretreated biomass suspension in hydrolysis reactor, equipped with pH and temperature control. Hydrolysis reaction was performed for three hours. The amino acid concentrates were separated from the residual biomass by centrifugation. Subsequnetly, free amino acids were detected by using o-phthaldialdehyde (OPA) method. Total protein content of the microalgae biomass was determined according the Lowry method following on alkaline extraction with 1 M sodium hydroxide, using Bovine Serum Albumin (BSA) as standard.

Compared to the control, the PEF-treated microalgae biomass resulted in an increase of the degree of hydrolysis by 10% to 40%, depending on biomass cultivation and storage conditions.

Funding: Horizon 2020, SABANA

2.1.4 Post-PEF-treatment incubation as a strategy for reduction of energy input

Contact: Dr. Aude Silve

In the past years, successful lipid recovery from the fresh microalgae *Auxenochlorella protothecoides* has been demonstrated using PEF pre-treatment and subsequent solvent extraction with hexane/ethanol blends. Performing immediate extraction, an energy of 1.5 MJ per kilogram of dry weight of microalgae (1.5 MJ/kg_{DW}) was required to achieve total lipid extraction, i.e. already lower than the lowest reported values for conventional techniques such as bead-milling or high pressure homogenization.

Recent results have shown that adding an incubation period after having applied PEF-treatment to the microalgae can considerably reduce the energy demand for PEF-treatment. All investigations were performed on fresh microalgae biomass cultivated at our institute. Directly after harvesting, microalgae were concentrated to 100g of dry weight per liter and treated with PEFs in a continuous flow setup in order to be as close as possible to real-time industrial processing.

Following PEF-treatment, the microalgae suspension was incubated under inert conditions, i.e. covered with nitrogen and kept in the dark. After a given incubation time, ranging from 10 minutes to 20 hours, the microalgae were centrifuged. Conductivity and carbohydrate content of the supernatant were quantified and the microalgae pellet was further submitted to lipid extraction. For all PEF-treatment energies tested, the amount of ions and carbohydrates released into the supernatant increased with incubation time.

Additionally, incubation had an overwhelming effect on lipid extraction yield (figure xxx). For the previously applied standard energy input of 1.5 MJ/kg_{DW}, maximum lipid yields are obtained after about 1 hour of incubation. When incubating the samples for 20 hours, similar yields can be obtained using only 0.25 MJ/kg_{DW} i.e. about 6 times lower than the lowest reported values in the literature so far. By allowing significant reduction of operating costs, the strategy which was develop in our institute increases the potential benefit for industrial applications. Future work will focus on clarifying how the biomass evolution during incubation facilitates extractions processes. This will enable further optimization of the complete microalgae downstream processing chain.

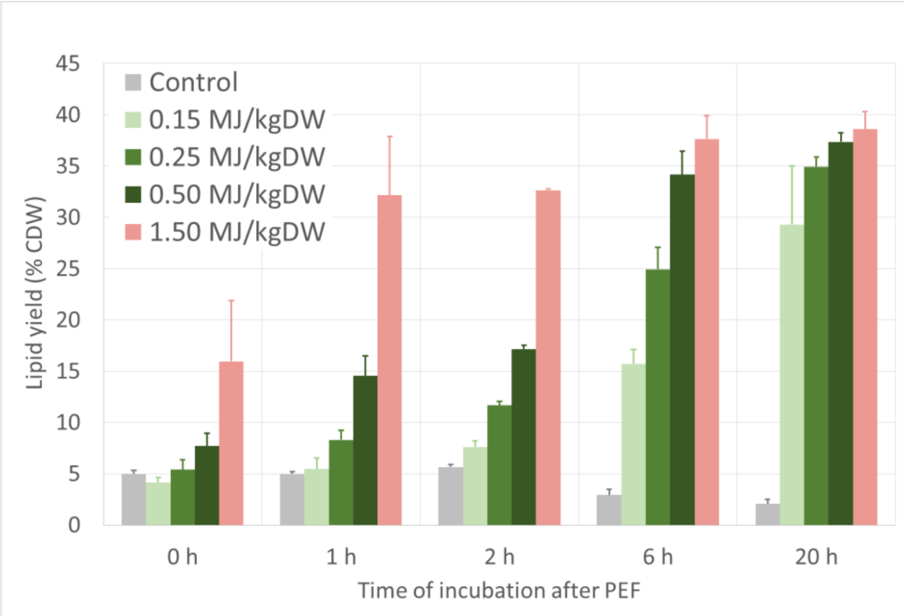


Fig. 2.1.1: Lipid extraction yield as a function of the duration of incubation after PEF-treatment and for different specific PEF treatment energies. Incubation was performed in an inert atmosphere with samples covered with nitrogen, and stored in the dark at 25°C. For each sample, time zero corresponds to the end of the PEF–treatment. Results are the average + std of 3 independent experiments.

Funding: H2020 SABANA

2.1.5 Biogas production from residual microalgae biomass fractions

Contact: Dipl.-Ing. Ralf Straessner

On this topic we investigated the possible energy gain from residual microalgae fractions by anaerobic digestion (AD). Different residual fractions of microalgal biomass from Auxenochlorella protothecoide (A.p.) were evaluated for methane yield and fermentation kinetics: a) untreated microalge, b) PEF-treated microalgae, c1) PEF-treated with replacement of the supernatant, directly after treatment by deionized water, c2) PEF-treated with replacement of the supernatant, after two and a half hour diffusion time, by deionized water and d) PEF-treated and subsequent lipid extracted microalgae. After treatment, the mentioned samples were transferred to Umweltforschungszentrum (UFZ) in Leipzig. The different microalgae samples were subjected to appropriate microorganisms (anaerobic bacterial communities) in biogas reactors. The continuous production of biogas, which consists of 55-90% of methane, in the AD-reactors was recorded, until biogas generation tend towards zero, which happened approximately after 6 weeks.

The investigation showed differences in the behavior of biogas generation, in the final production quantity and the kinetics, as well. It turned out that untreated microalgal biomass (sample a) was fermented faster, showing the earliest start of AD- process and hence biogas production but were limited in the final production volume, showing the smallest total produced biogas volume, except the lipid extracted sample d). The lipid extracted sample d) showed comparable starting behavior of the AD-process as the untreated control sample a) but exhibited the smallest amount of final produced biogas of all investigated specimen. In this case the extracted lipid fraction cannot contribute to the biogas generation. Lipids own the highest amount of specific energy among the other microalgal components (carbohydrates and proteins) and for that reason the drop of biogas production compared to the other samples was significant.

Samples c1) and c2) showed the longest lag period at the beginning of the AD-process. Most probably this is caused by the presence of the lipids in these biomass fractions. Inhibition of anaerobic digestion with the used bacteria, caused by LCFAs (Long Chain Fatty Acid) is a well-known effect, reported in the literature (Ma et al., 2015; Montingelli, Tedesco, & Olabi, 2015; Zonta, Alves, Flotats, & Palatsi, 2013).

The PEF treated sample b) with no further modification, showed an intermediate retarded start of the AD-process, being faster than the samples with removed supernatant c1 and c2, but slower than samples a) and d) at the beginning. At the end of the AD-process the amount of produced biogas with sample b) was only slightly higher than those of the untreated control sample a).

In summury it was shown that residual biomass, after PEF treatment and subquent product extraction, can be efficiently used for biogas production by AD process. The outcome of this investigation is specific for the used A.p. and the applied anaerobic bacterial community and may differ from other examinations with different microalgal biomass and different anaerobic microorganisms.

2.1.6 NewAlgae – nsPEF stimulation of Spirulina biomass

Contact: Dr. Christian Gusbeth

New sustainable food formulations based on algae protein NewAlgae: The main objective of the project is to facilitate process innovation in the food industry focused on algae protein. The focus of the project is on developing innovative processes along the algae value chain, leading to product development. Main task is to acquire technological insights into nsPEF-boosted cultivation and to characterize functional and bulk proteins from microalgae. In 2017 the work was focused on optimization of cultivation systems on lab-scale for the protein producing model strain *Arthrospira platensis* (commonly known as *Spirulina*) and the combination of the lab scale photobioreactor with nsPEF treatment in order to increase cell proliferation.

Cultivation experiments and the screening of suitable cultivation media allowed for a reduction of the conductivity from 18 $mS \cdot cm^{-1}$ to 10 $mS \cdot cm^{-1}$, which enabled nsPEF trials. After establishing the treatment procedure, equipment consisting in a Blumlein pulse generator and treatment chamber was build and provided to ETH Zürich for additional investigations. Now, for better statistics, parallel experiments could be carried out at ETH and KIT-IHM. The project is currently on track and first growth stimulation results were obtained for *A. platensis*.

Funding: WFSC Coop Research Program

2.1.7 DiWaL

Contact Dr. Wolfgang Frey

The aim of this project is bacterial decontamination of industrial processing water streams by pulsed electric field (PEF) treatment, in particular in electrocoating lines of the automotive industry. During the joint project, PEF technology will be integrated into a new, automated and resource-efficient water management concept for pretreatment and electrocoating lines. This will improve the circulation of water in the factory, avoid the use of biocides and reduce fresh water consumption. The joint project started in February 2017.

First task was to identify a non-impact parameter range, within which coating quality is not affected by PEF treatment. In the course of this, PEF treatment was applied for the first time to electrodeposition paints and water in anodic and cathodic electrocoating. It could be demonstrated, that PEF treatment with short unipolar pulses does not affect coating quality, even at high specific treatment energies. In the further course bipolar pulse protocols for both types of electrodeposition paints will be tested.

Second task is the development and manufacturing of a 30 kV / 0.6 kA solid state pulse generator. At current state a full-load test of 1 kV moduls was successful. An 8 kV test generator, consisting of eight moduls, is assembled and in test phase.

Additional, model calculations to integrate PEF technology into the dip coating process were carried out. It was found that in case of PEF-treatement in bypass operation mode, a rather low inactivation rate and a high flow rate is more efficient than a high inactivation rate at reduced medium flow. It was shown that an inactivation rate of 2 log reduction in bypass operation mode is sufficient to inhibit bacterial proliferation, whereas an increase of the mass-flow at 2 log reduction directly increases the inactivation performance in the entire volume of the dip coating bath. These findings provide an important approach for further energy optimization of the PEF treatment in electrodecoating lines.

Funding: Federal Ministry of Education and Research – BMBF; WavE program

DiWaL

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

NaWaM WavE

2.2 Components and electroporation processes

Contact: Martin Sack

2.2.1 ZIM-Wine

In the frame of the joint research project “PEF-treatment of crushed grapes (Elektroporation von Traubenmaische)” a device for the treatment of crushed grapes by pulsed electric fields (PEF) with a flow rate of 10t/h is currently being developed in collaboration with the industrial partners ARMBRUSTER Keltereitechnologie and KEA-TEC. The project is supported by the Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag.

The pulse circuit of the device comprises two Marx generators, each connected to one pair of electrodes inside the electroporation reactor. For efficient operation the design requires synchronized switching of the generators, which will be achieved by a triggered operation. For long-term operation a trigger generator operating without a separate trigger electrode has been developed. An over-voltage pulse is applied to the ground-side spark gap switch of each Marx generator causing ignition. The trigger has been tested in a test bed. Fig. 2.2.1 shows the trigger signal together with the light emitted from the triggered spark gap switch as a superposition of 20 single trigger events measured at a pulse repetition rate of 22 Hz. The trigger delay time for the selected parameter set has been measured to be approximately 130 ns and the jitter is sufficiently small.

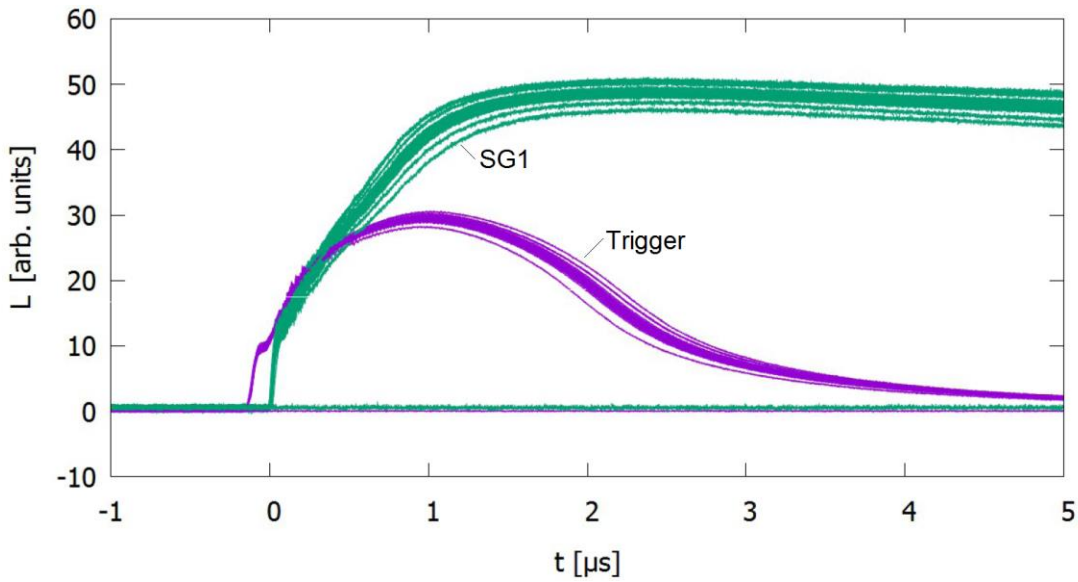


Fig. 2.2.1: Trigger signal together with a signal of the light emitted from the triggered spark gap switch as a superposition of 20 single trigger events.

In the frame of a scale-up of the existing electroporatrion device KEA-WEIN to a flow rate of 2 t/h in 2016, nozzles have been inserted to guide the nitrogen gas towards the gaps between the electrodes of the spark gap switches. Now, the operating performance of the device has been evaluated. Therefore, the device has been operated with different parameter settings up to the design limits. As an example Fig. 2.2.2 shows the voltage per stage when operating the device at maximum charging current of 1.4 A and approximately 50 kV ignition voltage of the spark gap switches. A pulse repetition rate of 45 Hz has been achieved.

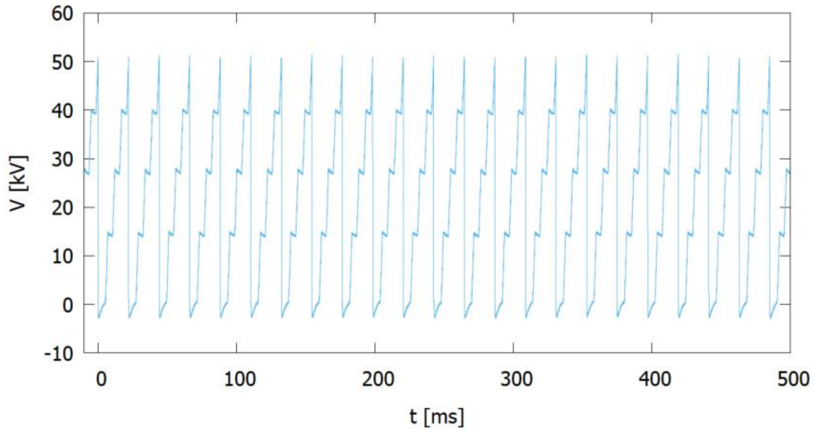


Fig. 2.2.2: KEA-WEIN: Stage voltage when operating the device at maximum charging current of 1.4 A and approximately 50 kV ignition voltage of the spark gap switches.

Collaboration: ARMBRUSTER Keltereitechnologie, KEA-TEC

Funding: The project is supported by the Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag.

Supported by: Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag

2.2.2 Marx-type pulse generator for stepwise arbitrary waveform generation

Contact: Dr.-Ing. Martin Sack

Currently a 150-stage pulse generator for stepwise arbitrary waveform generation to drive the Pulsed Electron Beam Device (GESA) is under development. In order to validate the design of the stage modules, an 8-stage generator has been set up. Fig. 2.2.3 shows a photo of the test setup. The stages are arranged in such a way, that the current path forms a helix. Each stage comprises a capacitor and an IGBT switch together with a bypass diode. A microcontroller at each stage enables individual toggling of each stage switch, synchronized to a trigger event common for all stages. Fig. 2.2.4 shows a stepwise arbitrary voltage shape measured at the generator's output and the current through a resistor connected to the terminals of the generator. A peak current of 600 A and a current rise time of 106 ns at 600 A have been achieved.

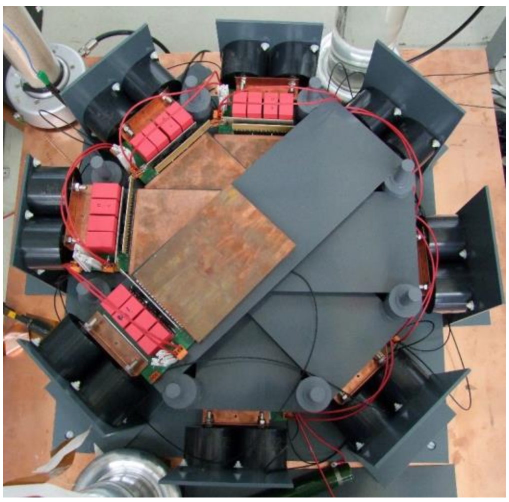


Fig. 2.2.3: 8-stage Marx-type generator for generation of stepwise arbitrary voltage.

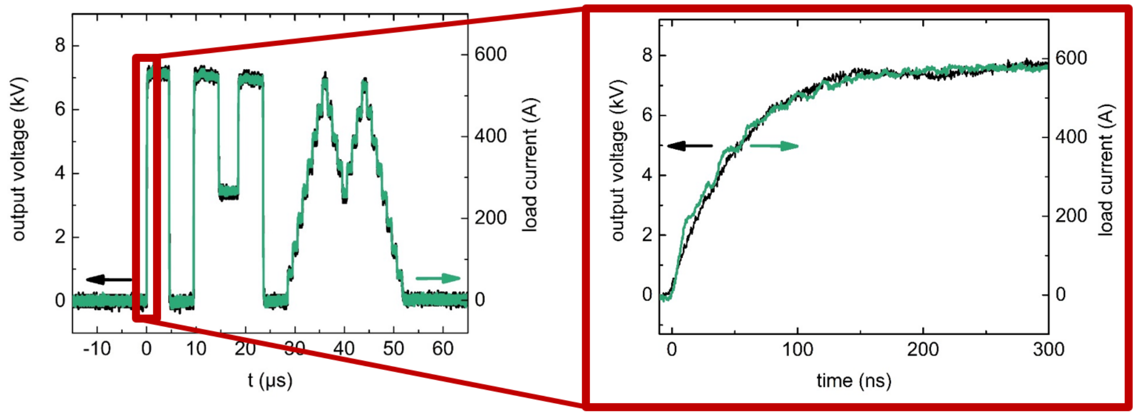


Fig. 2.2.4: Generation of a stepwise arbitrary voltage and magnified voltage- and current rise.

2.2.3 Marx-type pulse generator for bipolar rectangular pulses

For a project on the reduction of microbial contamination by applying a pulsed electric field a semiconductor-based Marx generator for repetitive generation of bipolar rectangular pulses is currently under development. The generator consists of stacked modules, thereby each module comprises an H-bridge topology enabling the generation of bipolar pulses. Each module is capable of delivering a rectangular pulse with a length in the range of between 1 µs and 10 µs at a voltage of up to 1 kV and a current of up to 600 A. In order to test the modules an 8-stage generator has been set up. Thereby, the generator has been grounded at its center to obtain ground-symmetric pulses to feed an electroporation reactor with an electrode system of parallel-plate type. Fig. 2.2.5 shows a photo of modules mounted inside the housing and an example for a pulse shape.

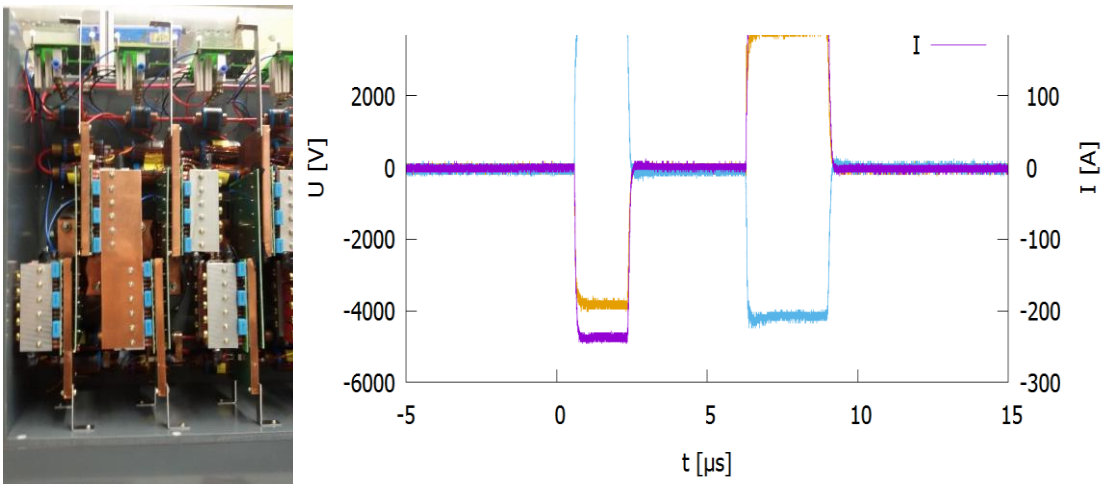


Fig. 2.2.5: Marx-type pulse generator for bipolar rectangular pulses: H-bridge modules mounted inside a housing (left) and example for a bipolar, ground-symmetric pulse shape.

2.3 Concentrating solar power (CSP)/ Liquid metal – Material research – improving the compatibility of materials for CSP

Contact: Dr. Alfons Weisenburger

Liquid metals as advanced heat-transfer- and storage media for CSP are a promising research area that will result in performance and efficiency increase and reduced costs. Different institutes and laboratories of the KIT therefore combine their long-standing experience and specific expertise in material research, system engineering, safety and thermal-hydraulics to tackle all relevant aspects of liquid metals as HTM. The IHM is especially focusing on compatibility research by surface optimization of existing materials using GESA and development of new materials that are able to form protective alumina scales.

2.3.1 Multipoint vacuum arc as cathode plasma source for sub-millisecond operation of GESA-facilities

The extension of the field of application of GESA facilities to non-adiabatic material treatment with sub-millisecond high-energy electron beams requires a comprehensive modification of the cathode. In the new cathode design, the plasma generated by vacuum arc discharges at the tips of several carbon fibers serves as electron source. At a maximum allowed load of the individual fibers of 1 A, it is possible to achieve emission current densities up to 0.5 A/cm². For a typical beam compression of K=10-16, this results in power densities at the target of up to 0.7 MW/cm² over pulse durations up to ~450 µs.

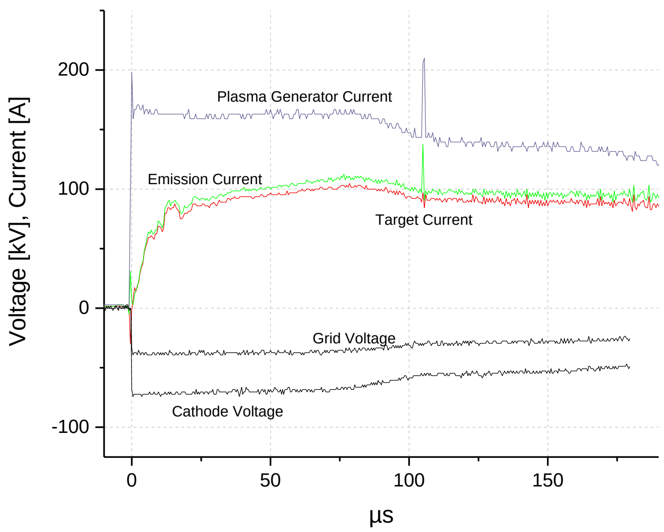


Fig. 2.3.1: Voltages and currents waveforms as function of time for typical sub-millisecond GESA pulse

The GESA concept with relatively low current density at the cathode and strong beam compression has the advantage that the cathode can be operated at relatively low plasma density. Thus, the formation of cathode spots at the metal surfaces that are in contact with the plasma can be controlled more easily. Using optical diagnostics, the ignition behavior of the vacuum arcs and the dynamics of the plasma was investigated. The findings enabled an optimization of the electrode geometry and potential distribution in order to generate a homogeneous cathode plasma.

2.3.2 Material development

Safe and economic operation of a CSP system requires enhanced compatibility of the selected liquid metal (Sn, LBE, or Na) with existing and new advanced materials for both targeted temperature regions (650 °C and higher). Beside the construction of experimental facilities that allow thermal cycling and corrosion tests in stagnant and flowing Na, the focus on material development was on high entropy alloys (HEA) and alumina forming austentic (AFA) steels. The ladder will be reported in section 3.1 of this report. HEA are a promising new class of materials for high temperature application in extreme environments like expected in liquid metal CSP systems.

In order to form FCC structure alloys with different compositions were calculated and finally 9 HEAs were produced. Six model HEAs contain four elements: Al, Cr, Ni and Fe, and three others contain five elements, Al, Cr, Fe, Ni with addition of either Cu or Ti or Nb. Most of these alloys obey the rules of FCC formation.

The model HEAs from FeCrAlNiX system (X: Ti, Nb, Cu) were prepared using high purity elements (99.95% or more) by arc-melting process with a non-consumable tungsten electrode under argon atmosphere (~0.9 atm). The prepared alloy ingots were flipped over and remelted at least five times in a water-chilled copper mold to facilitate alloy homogenization.

All the HEA alloys contain higher amounts of Al and Cr compared to the AFA. HEA with Al content higher than 4 wt% and without Cu addition showed good compatibility even the content of the highly soluble Ni is above 35 wt%.

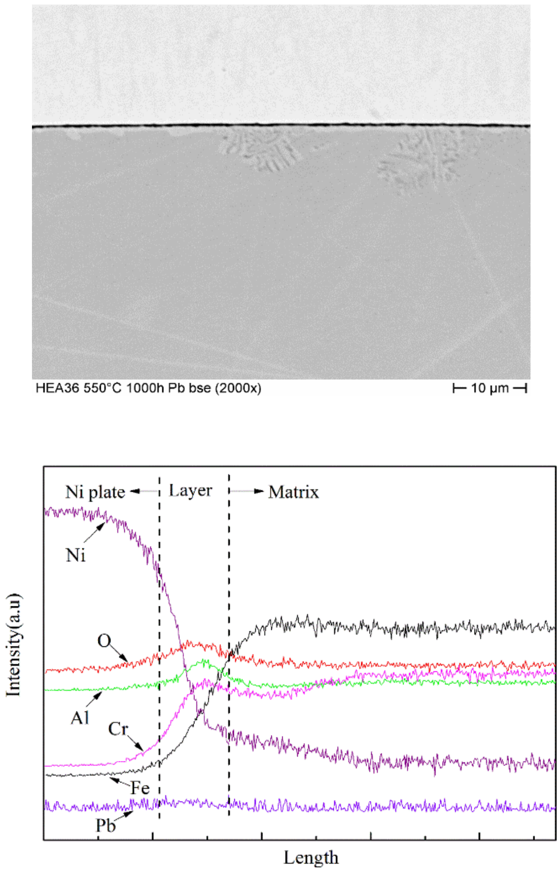


Fig. 2.3.2: SEM cross section (above) and elemental depth profile (below) of HEA exposed to Pb at 550°C for 1000h showing the formation of a protective Al-oxide scale

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Journal Publications

Sack, M.; Mueller, G. (2017). Design considerations for electroporation reactors. IEEE transactions on dielectrics and electrical insulation, vol. 24 (4), 1992–2000.

Onea, A.; Hering, W.; Reiser, J.; Weisenburger, A.; DIez De Los Rios Ramos, N.; Lux, M.; Ziegler, R.; Baumgartner, S.; Stieglitz, R. (2017). Development of high temperature liquid metal test facilities for qualification of materials and investigations of thermoelectrical modules. IOP conference series / Materials science and engineering, 228 (1), Art. Nr.: 012015.

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3 Safety Research for Nuclear Reactors (NUSAFE): Transmutation -Liquid Metal Technology-

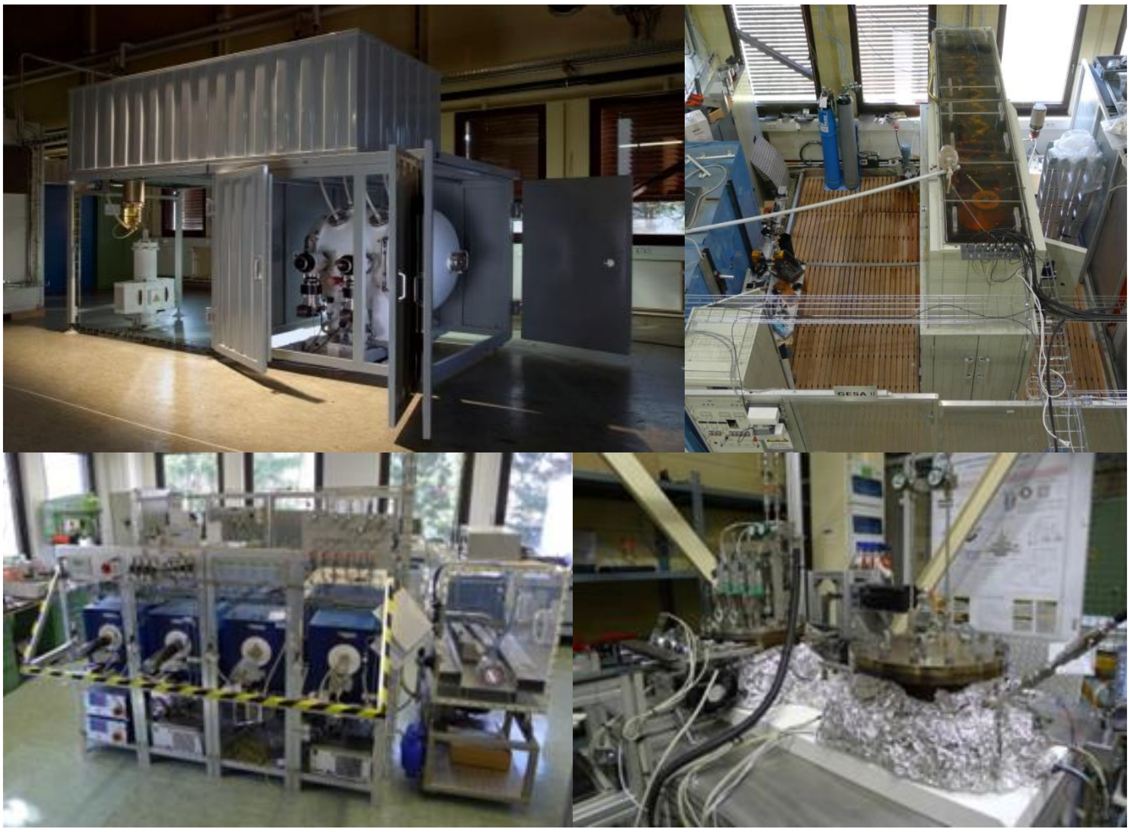
Contact: Prof. Georg Müller

Long-living high-level radioactive waste from existing nuclear power reactors should be transmuted in short-living radio nuclides using fast neutrons provided by a spallation target in an accelerator driven subcritical system or by a fast nuclear reactor. The objective is to reduce the final disposal time of high-level radioactive waste (plutonium, minor actinides) from some 10^6 years down to about 1000 years. Lead (Pb) and lead-bismuth (PbBi) are foreseen as spallation-target and coolant of such devices.

The aim of the institute's contribution is the development of advanced corrosion mitigation processes especially for parts under high loads like fuel claddings or pump materials in contact with liquid Pb or PbBi. Pulsed large area electron beams (GESA) are used to modify the surface of steels such that they fulfill the requirements of their surrounding environment. Corrosion test stands for exposure of specimens under relevant conditions are developed and operated. Conditioning the Pb-alloy with regard to its oxygen concentration and the transport of oxygen in PbBi are additional aspects of the work.

All tasks are embedded in European and international projects and cooperations like e.g., MaTISSE, MYRTE and GEMMA.

The most relevant results obtained in the reporting period are briefly presented:



3.1 Material development and advanced corrosion mititgation for heavy liquid metal-cooled nuclear systems

Contact: Dr. Alfons Weisenburger

3.1.1 Simulation study of cylindrical GESA

In order to modify tubular specimens at their surface and improve specific material properties, the pulsed electron accelerator GESA in cylindrical geometry with radial converging electron beam is investigated. The previous facility GESA IV was revised and a new design with a 1 m long cathode was developed at the Efremov Institute in St. Petersburg, Russia. Simulations of the electron beam characteristics performed at IHM showed two different operation regimes of the new facility: stable operation with homogeneous beam profile for low cathode-grid voltages and unstable operation with the formation of a virtual cathode between grid and anode for large cathode-grid voltages. Recently, the new accelerator was put into full operation. Although the cathode and grid voltages were chosen to obtain stable operation, first experiments showed an inhomogeneous beam profile and an enhanced current to the grid. These results triggered an advanced simulation study of the operation of the coaxial triode system, investigating the effect of electrons that pass by the anode and circulate inside the accelerator. The number of electrons missing the anode on their first approach depends on the azimuthal velocity distribution at emission, which is determined by the temperature of the cathode plasma. Because the electrons that pass by the anode circulate until striking the control grid, their residence time in the free space of the accelerator and thus their effect on the operation strongly depends on the grid transparency. It was found that circulating electrons shift the limit of the stable operation regime to much lower beam currents. Additionally, the beam profile becomes inhomogeneous and the electron current to the grid increases.

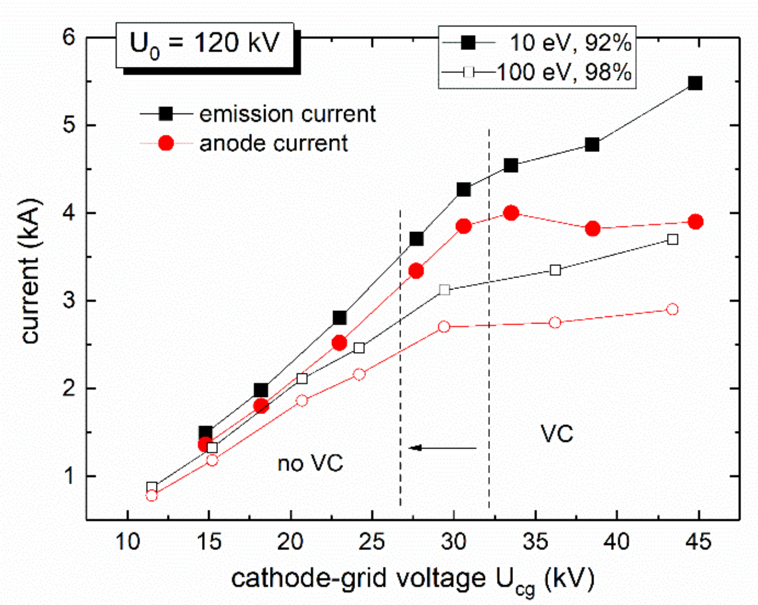


Fig. 3.1.1: Simulated emission and anode currents as function of cathode-grid potential without (closed symbols) and with (open symbols) the influence of circulating electrons.

3.1.2 MATISSE (Materials´ Innovations for Safe and Sustainable nuclear in Europe)

The MATISSE project aimed for the development of GENIV materials. The IHM was involved in three tasks; the development and testing (erosion/corrosion test in CORELLA) of MAXPHASE materials, the improvement of existing ODS by GESA and testing of ODS in Pb alloys under accidental conditions and the development of advanced corrosion barriers based on FeCrAl compositions. The project ended in 2017 and the IHM contributed to one deliverable concerning MAXPHASE materials, and were responsible for two other ones on ODS testing and corrosion barriers develoment.

All the MAXPHASES did not show any erosion/corrosion attack from the CORELLA tests (500°C 1000h) in contrary to the 316 steel reference samples. The best behviour of the tested MAXPHASE showed the $(Nb_{0.85},Zr_{0.15})_4AlC_3$ alloy were absolutely no signs of erosion corrosion could be observed.

The ODS related work concerned their behavior in liquid lead under transient conditions and off-normal conditions like high temperatures as well as under low oxygen conditions. ODS materials used are samples from 9Cr and 12Cr ODS plates in two conditions; as received or with a pulsed electron beam surface treatment (GESA). The latter was applied to remove impurities in the near surface region that are actually discussed as source for local corrosion attack. Additionally, some 14Cr ODS steel sample and specimens with Al alloying into the surface were tested.

After longer exposure time (5000h) at higher temperature (650 and 700°C) both steels 9 and 12Cr ODS with and without GESA treated surface showed dissolution attack. Al alloying in the surface by GESA had a clear positive effect. After 5000h at 650°C no dissolution attack and no thick oxide layer was found.

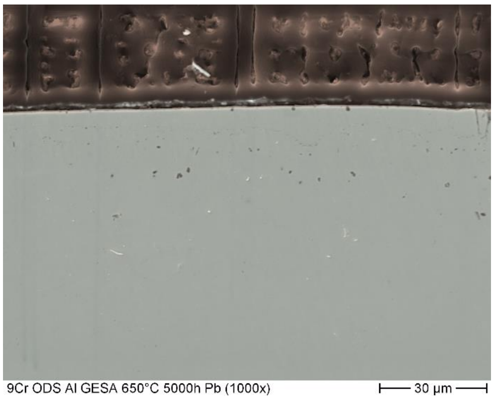


Fig. 3.1.2: SEM cross section of Al-surface alloyed 9Cr-ODS after exposure to Pb at 650°C for 5000h. No dissolution attack due to formation of thin Al-rich oxide scale.

The rapid cooling after the GESA treatment results in a columnar structure that seems to favour diffusion along grain boundary, which can deteriorate the corrosion behaviour. A positive effect by GESA was found on the 14Cr ODS steel at 650°C and 10^{-6}wt%O in the liquid Pb where local inner diffusion was prevented. The temperature transient test 550°C-750°C (24h) -550°C showed no influence on the corrosion behaviour. After an increase to 1000°C, the thick oxide layers spalled off. The thinner oxide layer on the GESA samples seems to be a bit more stable. Results are described in the MatISSE deliverable D4.3.2

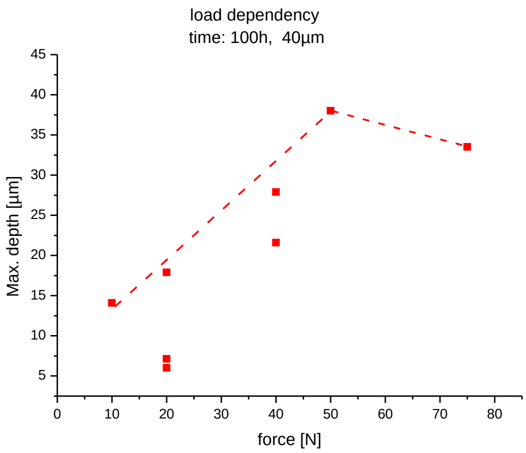
The focus of the advanced corrosion barrier development was on the development and optimization of FeCrAl alloys. Avoiding the formation of Cr-carbides by controlling the C content and the ratio between RE like Ti and Zr e.g. and C is one of the key issues for the formation of protective Al-rich scales. 10wt% Cr and 4 wt% Al, given that the RE and C concentrations are strictly controlled and optimized are the values to be respected. These results show that it is feasible to design ductile alumina-forming FeCrAl alloys as construction materials in corrosive environments at temperatures as low as 450°C. For Fe-Cr-Al-based alloys and modified surface layers exposed to molten lead with 10^{-6} wt.% oxygen in the 400-600°C temperature range an experimental criterion was defined concerning the aluminium and chromium content necessary to form a highly protective Al_2O_3 layer. It was found that higher Cr content leads to alumina formation at lower Al concentration. Outside this alumina stability domain, a concentration of 4 wt.% Al is sufficient, in synergy with 16 wt.% Cr content, to reduce drastically the growth rate of $Fe(Cr,Al)_2O_4$ sub-layer with spinel structure, on Fe-Cr-Al alloys exposed to oxygen-containing molten lead. Results are described in the MatISSE deliverable D5.2.1

Collaboration: SCK-CEN, ENEA, KTH, SANDIVK, CEA, …

Funding: EU-Project and NUSAFE

3.1.3 MYRTE (Multi-Purpose Hybrid Research Reactor for High Tech Application)

The IHM is performing fretting tests of wire wrapped fuel cladding samples designed for MYRRHA reactor. Therefore, the existing fretting test facility FRETHME was adapted to the MYHRRA relevant geometry and simultaneously completely overhauled. Fretting tests are conducted at 400°C hot liquid PbBi with a target oxygen content of 10^{-7} wt%. The amplitudes of the relative movement varied between 5 and 300 µm and the loads between 5 and 75 N. All tests are done at a frequency of 10 Hz with a duration between 100 h and 500 h and in cross orientation (contact point) of wire and tube, because previous experiments revealed that only this orientation provides trustworthy results.



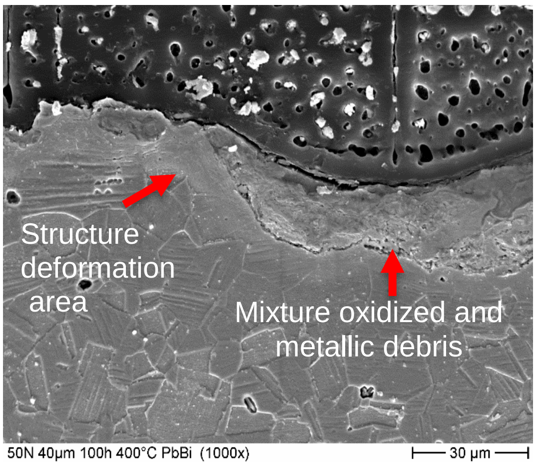


Fig. 3.1.3: Max. fretting depth as function of contact load (left) and etched SEM cross section of fretting area (right).

The maximum fretting depth is increasing with an increasing load up to 50N and decreases by a further increase of the laod. This phenomena can be explained with a required threshold pressure for the debris retention in the fretting area that acts as a kinf of protection layer. Fig. 3.1.3 shows a cross section though a fretting area. The debris is a mixture of oxidized and metallic debris, whereas the amount of metallic debris is increasing to the transition to the bulk material.

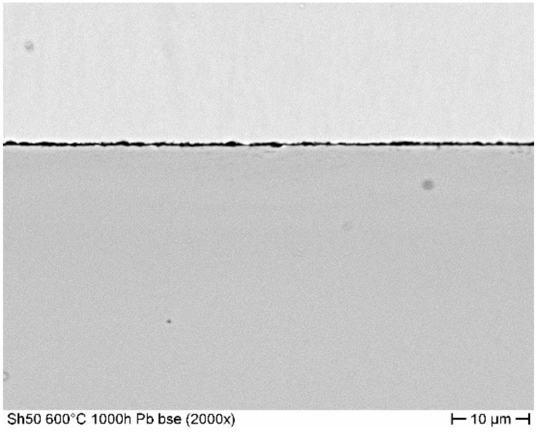
Funding: EU Project and NUSAFE

3.1.4 GEMMA

Based on the state of art in alumina-forming austenitic steels, 13 model alloys with Al, Cr, Fe and Ni are designed and prepared. The addition Al (2wt.%~ 5wt.%) aims to form alumina rich oxide scale at elevated temperature; Cr (12wt.%~ 16wt.%) plays a role of "third element effect" and Ni (20wt.%~ 32wt.%) is added to stabilize the austenitic structure. In addition, phase compositions of these models at 550°C and 600°C are also calculated by Thermo-Calc in order to make sure the austenite dominated structures at the test temperature range.

Compatibility with liquid Pb

Only 6 AFA survived corrosion test at 600°C for 1000h in Pb. These surviving model AFA, formed alumina scales combined with chromia on top and contained a minimum amount of 2% Al and 16% Cr. As an example the cross section of a surviving AFA alloy is depicted in Fig. 3.1.4.



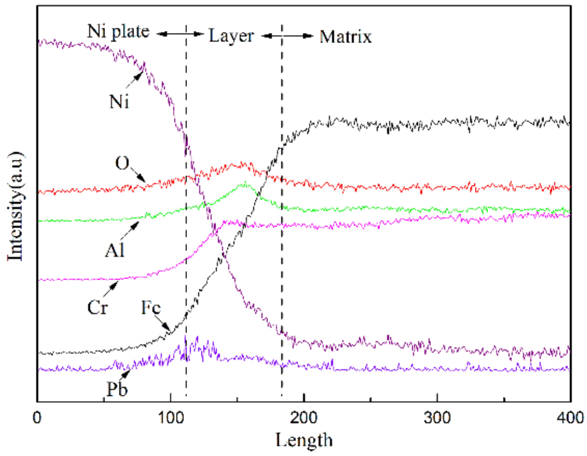


Fig. 3.1.4: SEM cross section (above) and elemental depth profile (below) of AFA exposed to Pb at 600°C for 1000h showing the formation of a protective Al-oxide scale.

Collaboration: IIT, ENEA, KTH, SANDIVK, SCK-CEN,

Funding: EU Project and NUSAFE

Involved Staff

DP W. An, A. Neukirch, Dr. R. Fetzer, Dr. A. Heinzel, Dr. A. Jianu, DI (Fh) F. Lang, **Prof. G. Müller**, Dr. G. Schumacher (Gast), H. Shi (CSC-PhD student), A. Sivkovich, **Dr. A. Weisenburger**, W. Zhen (CSC-PhD student)

Journal Publications

Fetzer, R.; An, W.; Weisenburger, A.; Müller, G. A. (2017). Pulsed electron beam facility GESA-SOFIE for in-situ characterization of cathode plasma dynamics. *Vacuum*, vol. 145, 179-185.

Fetzer, R.; An, W.; Weisenburger, A.; Mueller, G. (2017). Different operation regimes of cylindrical triode-type electron accelerator studied by PIC code simulations. *Laser and particle beams*, vol. 35 (1), 33-41.

4 Energy Efficiency, Materials and Resources (EMR): Energy-Efficient Processes -Multiphases and thermal processes-

Contact: Dr. Guido Link

Besides the activities on development of technologies and systems for the plasma heating in the FUSION Program, IHM is also in charge of research and development in the topic Energy Efficient Processes, part of the EMR Program.

An important part of this research is the dielectric characterization of the processed materials in the parameter range relevant to processes under development. Therefore existing test-sets are continuously improved and new test-sets are developed following the new requirements regarding materials compositions or process parameter range. Meanwhile a very versatile test lab for dielectric characterization exists. This allows temperature dependent dielectric measurements in the frequency range from 10 MHz to 30 GHz for low as well as high loss materials and from room temperature up to 1000°C for solids, liquids and at pressures up to 20 bar.

All this expertise and the existing industrial scale high power microwave infrastructure faces growing interest from industry and research. As a consequence the research group is involved in several national and international joint research projects with objectives in various fields of applications. The H2020 project SYMBIOBTIMA requests the design of an industrial prototype reactor for the microwave assisted depolymerization of PET plastic waste for the purpose of energy efficient recycling. In the frame of the H2020 Marie Curie international training network TOMOCON that started end of 2017 a microwave tomographic sensor will be developed. Within the German-Korean project REINFORCE the potential of microwave dielectric heating as well as microwave sustained plasma heating will be investigated with respect to energy efficient carbon fiber production.

Solid state microwave amplifiers getting more and more competitive compared to magnetron sources with respect to power and costs. Furthermore such amplifiers allow precise control not only of power level but also of frequency and phase and promise significant longer lifetime than magnetrons. Those features might be door openers for novel application that could not be satisfied with magnetron sources. Therefore national funded collaboration projects have been started with HBH microwave GmbH recently to develop affordable high power solid state generators that meet the requirements for novel process control concepts. Furthermore those novel microwave sources might be useful for microwave sustained plasma generators for plasma activation of CO_2 in the frame of research activities like Power to X. Therefore recently a novel lab for plasma chemistry using atmospheric microwave plasma has been established. The status of major projects is briefly introduced in the following chapters.

4.1 Materials Processing with Microwaves

4.1.1 SYMBIOPTIMA

Contact: M.SC. Vasileios Ramopoulos

The KIT task within the European project SYMBIOPTIMA is to support the development of an industrial scale and modular microwave reactor for the recycling of PET plastic waste. In this sense recycling means depolymerization of the PET molecules into monomers by use of microwave assisted alkaline hydrolysis. Further information about this project may be found under http://symbioptima.eu/ Based on the measured dielectric properties and using common 3D software tools, an optimized industrial scale and modular microwave cavity design has been developed. The cavity is designed for use in combination with an Archimedean screw to transport the reaction material within a cylindrical dielectric tube with a diameter of 250 mm. The proposed design is modular and can be easily scaled in length. The developed design offers a well-defined and homogeneous power distribution of a single 2.45 GHz magnetron source within the applicator and the process material. Results of various simulations show that a homogeneous heating of the process material in axial as well as azimuthal direction can be achieved by using the $TE_{1,0}$ field mode. The simulated design provides high energy efficiency with a reflected power of less than 10 %, insensitive to even significant variation of materials permittivity. The CAD model and a photo of the manufactured microwave cavity are shown in Fig. 4.1.1.

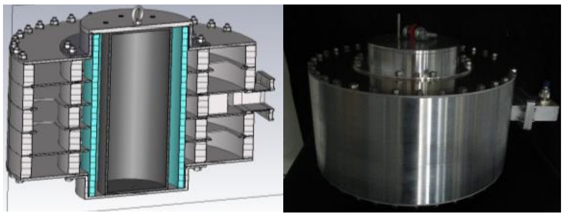


Fig. 4.1.1: Left: CAD model of the microwave cavity; Right: Experimental setup

For testing with a 800 W magnetron, a hollow cylindrical sample with 183 mm outer diameter and 171 mm inner diameter and dielectric parameters of $\epsilon'=15$, $\tan\delta=0.3$ was chosen. The measurement of the energy (temperature) distribution is carried out by an infrared camera FLIR type AX5. Fig. 4.1.2 shows the measured temperature distribution in comparison with the simulated absorbed power distribution within the sample. The measured temperature variation is found to be ± 8 °C at a mean temperature level of 90 °C. A proper agreement between simulation and experiment exists.

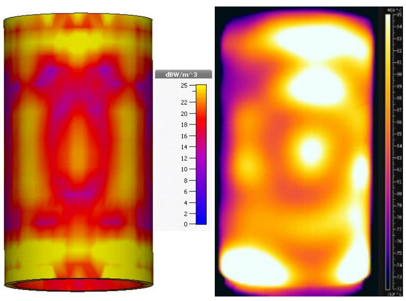


Fig. 4.1.2: Simulated power distribution (left), measured temperature distribution (right).

Funding: H2020-SPIRE-2015; grant agreement: 690426

4.1.2 InnoConTeMP

Contact: M.Sc. Dominik Neumaier

Microwave heating has a great potential to replace classical heating processes (e.g.: hot air). The main advantage of microwaves is the volumetric heating effect, which does not limit the heating process by slow thermal conduction. Compared to a classical heating system both energy consumption and cycle time can be significantly reduced in various applications. However, the application of microwave technology in industrial processes very of suffers from insufficient temperature uniformity of the heated product.

The aim of the technology transfer project InnoConTeMP (Innovative Control of Temperature Distributions for Microwave heating Processes) is to improve the temperature distribution of a workpiece in HEPHAISTOS systems of the industrial partner Vötsch Industrietechnik GmbH. A model predictive controller (MPC), which uses a thermodynamic model and the results of a Kalman filter, is used for controlling the temperature level as well as the temperature distribution in a workpiece. This is achieved by individual control of the power levels of the distributed microwave sources. The Kalman filter permanently observes the influence of the electric field and the material properties. The structure of the whole control algorithm is presented in Fig. 4.1.3.

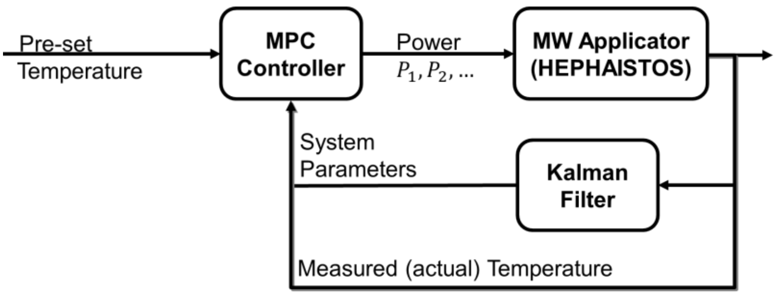


Fig. 4.1.3: Structure of the control algorithm.

Thereafter, an architecture was developed to integrate this algorithm in the existing S!MPAC controller of our partner Vötsch. The control structure is shown in Fig. 4.1.4. Alternatively, in case of limited CPU power of standard S!IMPAC controllers a more powerful industrial PC can be connected over TCP/IP. Thus the MPC and Kalman filter can be computed on this powerful PC and the results are sent to the S!MPAC. In addition to that, the new MPC controller can also be used and tested with the Labview control system, which was developed at KIT.

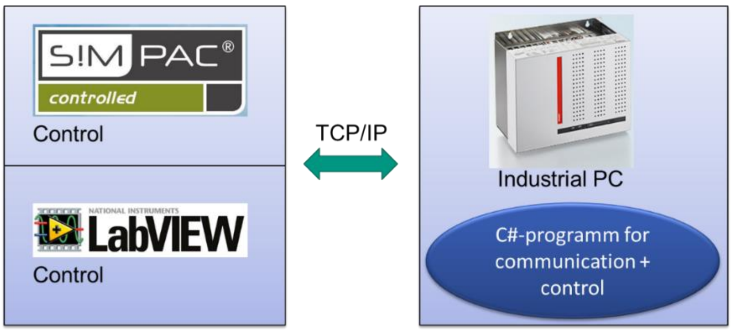


Fig. 4.1.4: Architecture of the whole control system.

Funding: KIT technology transfer project; project no.: N041

4.1.3 High power solid-state microwave generators

Contact: Dr. Sergey Soldatov

For industrial scale microwave processing, major issues are precise and stable process control as well as homogeneous heating of the products. This depends on the homogeneity of the absorbed power in the dielectric load, which, in its turn, depends on the electric field pattern as well as on the dielectric properties of the processed materials. The field patterns result from the superposition of the excited eigenmodes in the microwave oven. The use of solid state high power amplifiers instead of commonly used magnetron oscillators promises to get significantly more influence to the process control and temperature uniformity within the product. Those will not only allow control of the power amplitude like in magnetrons but also the precise control of frequency and phase correlation in-between different sources. A fast superposition of different specific field patterns, resulting from well-defined amplitude, frequency and phase variation, will allow to further improve temperature uniformity as compared to existing methods. This approach is illustrated in Fig. 4.1.5. This approach motivated a collaboration project with HBH microwaves GmbH, supported by the Federal Ministry for Economic Affairs and Energy (BMWi) that started in March 2017. A major objective of the project is the development of novel high power (~ 1 kW) solid-state microwave sources with fast computer control. Those sources will enable the variation of frequency within the ISM band from 2.4 GHz to 2.5 GHz, the variation of phase from 0 to 2π and the variation of power from 10 W to 1000 W at a time scale of 100 ms. To get the maximum use of that novel microwave sources, with respect to temperature uniformity in large scale applicators with distributed microwave sources, the MPC control concepts developed in InnoConTemp (see previous chapter) will be extended accordingly.

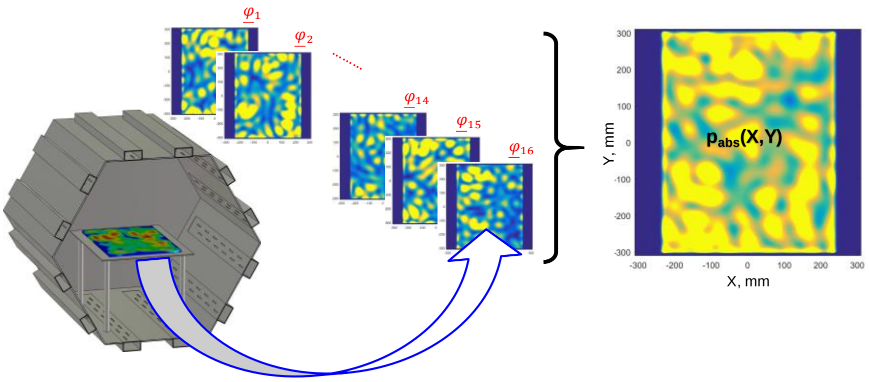


Fig. 4.1.5: Schematic pathway from non-controlled heating dominated by standing wave pattern towards homogeneous heating based on the intelligent control of launched power.

Another promising application of fast controlled microwave sources is the development of advanced microwave sustained plasma reactors, which is strongly motivated by the establishment of the "Closed Carbon Cycle Economy" and conversion of CO_2 into synthetic fuels. As it was proven in many experiments non-thermal CO_2 plasmas provide maximal conversion efficiency. Microwave sustained atmospheric plasmas can be operated far from the thermal equilibrium if the microwave energy is fed in short nanosecond pulses. Such pulsed operation prevents the thermalization of ions which happens at µs time scales. High power microwave pulsed in this timescale are not feasible with commercial vacuum electronic devices (magnetron). By use of high power solid-state amplifiers this timescale can be reached. First solid-state generators and experimental results will be expected in 2018.

Funding: ZIM cooperation project, support code ZF4204602PR6

4.1.4 REINFORCE

Contact: M.Sc. Julia Hofele

Due to the high tensile strength to weight ration of carbon fibers compared to steel and their lightweight potential, carbon fibers find increasing applications in the automotive and avionic industry. In 2014 the industry required a carbon fiber volume of 53 kt worldwide which is expected to increase to 100 kt in 2020. Until now, the carbon fiber production is rather expensive and energy intensive compared to the production of aluminum and steel.

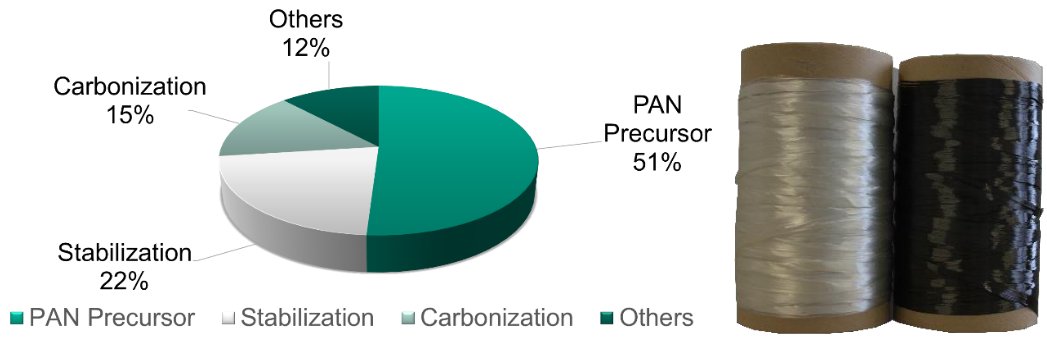


Fig. 4.1.6: Manufacturing costs of carbon fibers

The project REINFORCE, which started officially in September 2017, has the objective to improve the carbon fiber production. The three most time and energy consuming production steps, precursor creation, stabilization and carbonization, are to be optimized. A new PAN-precursor, which can be used for melt-spinning, will be developed by the Korean partners KCTECH, DongMyung Technologies and Yeungnam University. In the frame of REINFORCE, KIT is involved in the replacement of conventional heating in the stabilization and carbonization process by dielectric heating or microwave sustained plasma heating. It will be evaluated which method is more efficient and which has a better influence on the fiber properties compared to conventional heating. The development of an appropriate microwave applicator and the experimental investigation of potential advantages from dielectric and plasma heating are performed at IHM. In a first step, different PAN fiber samples and a stabilized fiber have been characterized dielectrically. Ideally, the information of the dielectric properties can be used to evaluate the end of the stabilization process. The next steps include first experiments in the cavity that was also used for the dielectric measurements in order to get a better understanding of the process. Finally, microwave applicators will be built for dielectric heating and plasma heating in order to stabilize the fiber. Final results of the project are expected in 2020.

Sample	Fiber Tow	Dielectric Constant ε_r'	Dielectric Loss Factor ε_r''
PAN Company A	12k	3.9	0.005
PANOX Company A	12k	5.8	0.012
PAN Company B	3k	3.8	0.004

Table 4.1.1: Dielectric Properties at 2.45 GHz measured for virgin and stabilized PAN fibers

Funding: ZIM cooperation project; support code ZF4204603SY7

4.1.5 TOMOCON

Contact: Dr. Guido Link

The European Marie Skłodowska-Curie Training Network "Smart tomographic sensors for advanced industrial process control (TOMOCON)" joins 12 international academic institutions and 15 industry partners, who work together in the emerging field of industrial process control using smart tomographic sensors. The network shall lay the scientific and technological fundamentals of integrating imaging sensors into industrial processes and will demonstrate its functional feasibility on lab and pilot-scale applications.

15 doctoral researchers are being trained in the fields of process tomography hardware, software and algorithms, control systems theory and design, industrial process design, multi-physics modelling and simulation, human-computer interaction, and massive parallel data processing. Together with their supervisors and industry partners they are engaged in multi-disciplinary research on various tomographic imaging modalities, tomographic image processing as well as advanced multi-physics modelling of processes, sensors and actuators. Proof-of-principle demonstrations of tomography-based process control are being foreseen for important industrial processes, such as inline fluid separation, microwave drying of porous materials, continuous steel casting and ultrasound-controlled crystallization. The doctoral researcher at KIT will be involved in the development of a microwave tomograph to detect the moisture distribution in a porous material and to use that information to get a feedback for the process control. The technology finally is planned to be demonstrated on a conveyor belt system for microwave assisted drying of polymer foams.

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Fig. 4.1.7: Hybrid HEPHAISTOS system for continuous processing of materials

Funding: H2020-MSCA-ITN-2017; Grant agreement 764902

Involved Staff

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Journal Publications

Link, G.; Ramopoulos, V. (2017). Simple analytical approach for industrial microwave applicator design. Chemical engineering and processing, 125, 334-342.

Sanz-Moral, L. M.; Navarrete, A.; Rueda, M.; Martín, Á.; Sturm, G.; Stefanidis, G.; Link, G.; Stefanidis, G. (2017). Release of hydrogen from nanoconfined hydrides by application of microwaves. Journal of power sources, vol. 353, 131–137.

Li, N.; Li, Y.; Jelonnek, J.; Link, G.; Gao, J. (2017). A new process control method for microwave curing of carbon fibre reinforced composites in aerospace applications. Composites / B, vol. 122, 61–70.

Appendix

Equipment, Teaching Activities and Staff

IHM is equipped with a workstation cluster and a large number of experimental installations: KEA, KEA-ZAR, three GESA machines, eight COSTA devices, one abrasion and one erosion teststand, two gyrotron test facilities with one common power supply and microwave-tight measurement chamber, one compact technology gyrotron (30 GHz, 15 kW, continuous wave (CW)), several 2.45 GHz applicators of the HEPHAISTOS series, one 0,915 GHz, 60 kW magnetron system, one 5.8 GHz, 3 kW klystron installation and a low power microwave laboratory with several vectorial network analysers.

The project FULGOR, targeting for a renewal of the KIT gyrotron teststand is progressing. In 2013, an agreement on the project structure including the involvement of the KIT project and quality management has been achieved. The final start of the procurement of the equipment was in 2014.

Prof. John Jelonnek has continued to teach the lecture course entitled “High Power Microwave Technologies (Hochleistungsmikrowellentechnik)” for Master students at KIT. Prof. Georg Müller has continued to teach the lecture on “Pulsed Power Technologies and Applications” at KIT. Dr. Gerd Gantenbein has been teaching the part “heating and current drive” of the lecture “Fusionstechnologie B” by Prof. R. Stieglitz, IFRT. Dr.-Ing. Martin Sack hold the lecture course “Elektronische Systeme und EMV” at KIT.

At the turn of the year 2017/2018 the total staff with regular positions amounted to 41 (20 academic staff members, 10 engineers and 11 technical staff member and others).

In addition 12 academic staff members, 1 engineer and 3 technical staff members (and others) were financed by acquired third party budget.

In course of 2017, 2 guest scientists, 12 PhD students (1 of KIT-Campus South, 8 of KIT-Campus North, 2 Scholarship, 1 in cooperation with IPP Greifswald), 1 DHBW student, 2 trainee in physics laboratory and 4 trainees in the mechanical and electronics workshops worked in the IHM. 5 Master students have been hosted at IHM and 6 Bachelor student has been at IHM during 2017.

Strategical Events, Scientific Honors and Awards

Felix Mentgen received the “Paul Wurth Award” for the best submitted master thesis.

Dr. Aude Silve received the “Alessandro Chiabrera Award for Excellence in Bioelectromagnetics” BioEM 2017 Koferenz in Hagzhou, China.

Prof. Manfred Thumm received the “IRMMW-THz Society Exceptional Service Award”.

Longlasting Co-operations with Industries, Universities and Research Institutes

- Basics of the interaction between electrical fields and cells (Bioelectrics) in the frame of the International Bioelectrics Consortium with Old Dominion University Norfolk, USA; Kumamoto University, Japan; University of Missouri Columbia, USA; Institute Gustave-Roussy and University of

Paris XI, Villejuif, France; University of Toulouse, Toulouse, France, Leibniz Institute for Plasma Science and Technology, Greifswald, Germany.

- Desinfection of hospital wastewater by pulsed electric field treatment in cooperation with University of Mainz and Eisenmann AG.

- Integration of the electroporation process for sugar production with SÜDZUCKER AG.

- Development of protection against corrosion in liquid metal cooled reactor systems in the following EU-Projectes: LEADER, GETMAT, MATTER, SEARCH (Partner: CEA, ENEA, SCK-CEN, CIEMAT).

- Development of large area pulsed electron beam devices in collaboration with the Efremov Institute, St. Petersburg, Russia.

- Experiments on liquid Pb and PbBi-cooling of reactor systems with the Institute for Physics and Power Engineering (IPPE), Obninsk, Russia.

- Development, installation and test of the complete 10 MW, 140 GHz ECRH Systems for continuous wave operation at the stellarator Wendelstein W7-X in collaboration with the Max-Planck-Institute for Plasmaphysics (IPP) Greifswald and the Institute of Interfacial Process Engineering and Plasma Technology (Institut für Grenzflächenverfahrenstechnik und Plasmatechnologie, IGVP) of the University of Stuttgart.

- Development of the European ITER Gyrotrons in the frame of the European GYrotron Consortium (EGYC) and coordinated by Fusion for Energy (F4E). The other members of the Consortium are CRPP, EPFL Lausanne, Switzerland, CNR Milano, Italy, ENEA, Frascati, Italy, HELLAS-Assoc. EURATOM (NTUA/NKUA Athens), Greece. The industrial partner is the microwave tube company Thales Electron Devices (TED) in Paris, France.

- Development of new diagnostic systems for improvement of electron guns for gyrotrons and cavity interaction calculations in collaboration with the St. Petersburg Polytechical University, Russia and the University of Latvia, Latvia.

- Development of Microwave Systems of the HEPHAISTOS Series for materials processing with microwaves with the Company Vötsch Industrietechnik GmbH, Reiskirchen.

The Institute for Pulsed Power and Microwave Technology (Institut für Hochleistungsimpuls- und Mikro-wellentechnik (IHM)) is doing research in the areas of pulsed power and high-power microwave technologies. Both, research and development of high power sources as well as related applications are in the focus. Applications for pulsed power technologies are ranging from materials processing to bioelectrics. High power microwave technologies are focusing on RF sources (gyrotrons) for electron cyclotron resonance heating of magnetically confined plasmas and on applications for materials processing at microwave frequencies.

The IHM is doing research, development, academic education, and, in collaboration with the KIT Division IMA and industrial partners, the technology transfer. The IHM is focusing on the long term research goals of the German Helmholtz Association (HGF). During the ongoing program oriented research period (POF3) of HGF (2015 – 2020), IHM is working in the research field ENERGY. Research projects are running within following four HGF programs: “Energy Efficiency, Materials and Resources (EMR)”; “Nuclear Fusion (FUSION)”, “Nuclear Waste Management, Safety and Radiation Research (NUSAFE)” and “Renewable Energies (RE)”.

During 2017, R&D work has been done in the following areas: fundamental theoretical and experimental research on the generation of intense electron beams, strong electromagnetic fields and their interaction with biomass, materials and plasmas; application of those methods in the areas of energy production through controlled thermonuclear fusion in magnetically confined plasmas, in material processing and in energy technology.

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