KIT SCIENTIFIC REPORTS 7758

Annual Report 2018

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

John Jelonnek (Ed.)

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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 2018, 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. Additionally, it is involved in research and development in the field of and on the application of microwaves to chemical processes, materials and composites.

In particular the following major activities have been carried out in 2018:

- 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 and experimental verification of advanced electron gun design.
- Gyrotron Development for DEMO, with the focus on increasing the operation frequency in a first step to 204 GHz and efficiency enhancement by multi-staged depressed collectors.
- Developments on theory and numerical simulations of beam-wave interaction tools to investigate After-Cavity-Interaction.
- FULGOR: progress in the construction of the new gyrotron test stand
- Generation of ultrashort pulses with new gyro-devices.
- Development of diagnostic tools to characterize magnetron injection guns for gyrotrons and generate high order TEmn modes

1.1 Gyrotron Development for W7-X

Contact: Dr. Konstantinos Avramidis

During the first experimental campaign (OP 1) of the stellarator Wendelstein 7-X (W7-X), the Electron Cyclotron Resonance Heating (ECRH) system, consisting of ten 1 MW, 140 GHz gyrotrons, performed remarkably well: the available EC heating and current-drive power in the plasma ranged from 7 to 9 MW, that is, W7-X is using the world's largest ECRH installation today. In view of the second experimental campaign (OP 2) in 2021, even higher ECRH power is desired; hence an upgrade of the ECRH system has been under consideration for some time. Motivated by this, studies on upgrading the existing 140 GHz, 1 MW $TE_{28,8}$-mode gyrotron towards 1.5 MW operation in the $TE_{28,10}$ mode are ongoing at IHM. In this period, the design of a $TE_{28,10}$ gyrotron launcher has been further optimised and high-quality excitation of the rotating $TE_{28,10}$ mode has been achieved in a dedicated mode generator, with counter-rotating mode content below 0.6 % (Fig. 1.1.1). The mode generator is now ready to test the gyrotron quasi-optical system whenever available.

In November 2018, the Scientific Board (Wissenschaftlichen Leitung) of IPP decided to proceed with the upgrade of the W7-X ECRH system, taking into account the request for higher EC power and the feasibility of the upgrade, as assessed by IPP, KIT/IHM and the industrial partner (Thales). With respect to the upgraded 1.5 MW gyrotron, a CW prototype and two series tubes are now planned. The contract with the industrial partner is expected to be signed in 2019 and IHM is expected to be strongly involved in the upgraded gyrotron development as well as in the related experimental tests. Funding by EUROfusion will also be pursued.

Since the gyrotron upgrade will be based on the existing $TE_{28,8}$ tube, a careful feasibility study and risk analysis have taken place, considering all the changes necessary for the upgrade. A preliminary time-schedule of the KIT activities has also been proposed (Table 1.1.1), under the assumption that the required development towards the upgrade will include a continuous wave (CW) prototype, manufactured by the industrial partner, as well as a short-pulse mock-up gyrotron for testing key components, manufactured mostly at KIT.

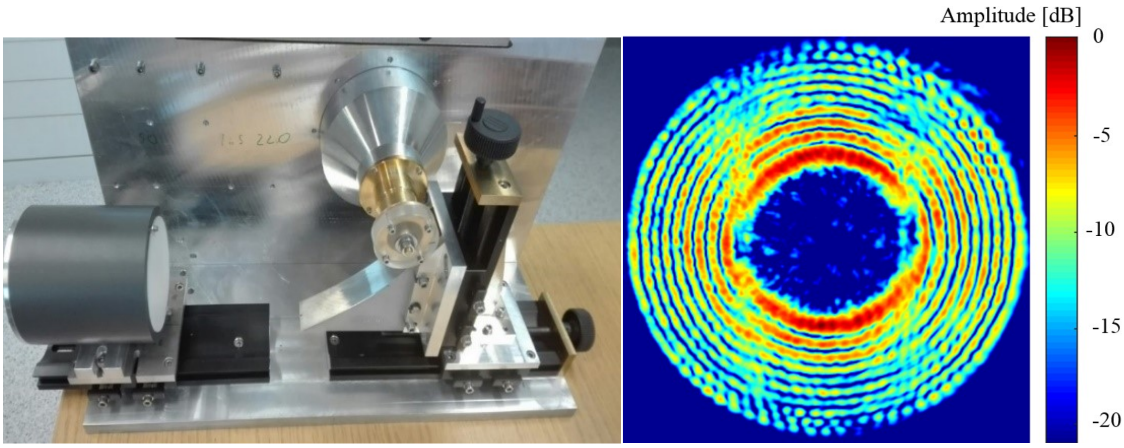


Fig. 1.1.1: Mode generator for the $TE_{28,10}$ mode (top) and measured normalized pattern (electric field amplitude – vertical polarization) of $TE_{28,10}$ at 140.155 GHz (bottom).

WBS	KIT Tasks	Duration (months)	Year 1 – Qt 1	Year 1 – Qt 2	Year 1 – Qt 3	Year 1 – Qt 4	Year 2 – Qt 1	Year 2 – Qt 2	Year 2 – Qt 3	Year 2 – Qt 4	Year 3 – Qt 1	Year 3 – Qt 2
WP1	**CW prototype**	**30**										
WP1.1	Finalise RF design of prototype and technical drawings	6										
WP1.2	Low-power tests of launcher & mirrors mock-up	6										
WP1.3	Support/follow-up of industrial contract between IPP-TED	24										
WP1.4	Testing of the prototype at KIT	6										
WP2	**Short-pulse pre-prototype**	**24**										
WP2.1	Design and technical drawings	6										
WP2.2	Manufacturing of components and assembly	9										
WP2.3	Testing of the pre-prototype at KIT *a. 1st verification of RF design*	3										
	b. Additional design verification / testing of improvement proposals	9										
WP0	*IPP-TED contract*	24										

Table 1.1.1: Indicative time-schedule of the envisaged KIT involvement in the development of the upgraded 1.5 MW $TE_{28,10}$-mode gyrotron.

A quasi-optical mode converter has been designed for an 1.5-MW gyrotron operating in the $TE_{28,10}$ mode at 140 GHz. A mirror-line launcher is used in the quasi-optical mode converter. The parameters of the launcher are chosen to provide the same Brillouin angle at the launcher aperture as that in the launcher for the $TE_{28,8}$-mode gyrotrons, so that the structure of the mirror system will be very similar to that of the mirror system integrated in the $TE_{28,8}$-mode gyrotrons. As the $TE_{28,10}$-mode gyrotron is operated at higher mode and higher power, it is very importment to check the peak ohmic loading on the launcher wall for the CW operation. Taking into account the roughness and the temperature of the launcher wall with ohmic loading, the simulation results show that the peak density of the ohmic loading is estimated as 477 W/cm^2 even with the enhancement factor of 1.8 used in the calculation, the total ohmic loss is about 1.88 %. A mirror system has been designed to change the parameters of the Gaussian-like RF beam radiated from the launcher to achieve a circular beam waists of 20.1 mm. The field distribution of the RF beam on the gyrotron window with radius of 44 mm is shown Fig. 1.1.2, where the Gaussian mode content of the RF beam is as high as 99 %. The power transmission of the quasi-optical mode converter is estimated as 98.3 %.

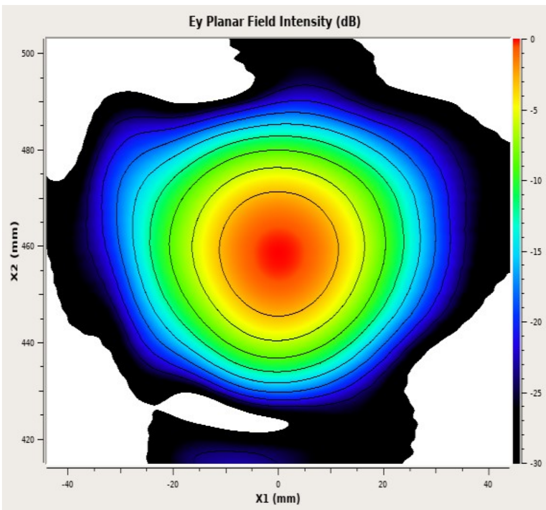


Fig. 1.1.2: The field distribution on the gyrotron window.

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 IHM team is working on the improvement of the conventional hollow-cavity gyrotron technology. The short-pulse 1 MW, 170 GHz gyrotron prototype for ITER, designed, fabricated and tested by KIT, presents very stable gyrotron operation at 170.1 GHz in the nominal cavity mode $TE_{32,9}$. The RF output power is above 1 MW with an efficiency slightly above 40 % in single-stage depressed collector operation (SDC). Further experiments with the 1 MW short pulse gyrotron have shown that the total efficiency of the tube can be improved by reducing the space-charge voltage depression of the electron beam. This may be achieved by introducing simple internal structures in the area of the mirror-box or by shifting of the retarding voltage closer to the collector (i.e. retarding voltage on the outer gyrotron body). Different types of such structures have been experimentally tested in the SP gyrotron increasing the total efficiency of the tube. The current goal is to find a solution, which would be compatible with existing CW gyrotron technology and could be easlily implemented in the next long pluse gyrotron. A suitable structure (Fig. 1.2.1) was proposed and experimentally tested, delivering a 12% increase of the efficiency compared to the regular gyrotron configuration. The comparision of all ac hieved results are presented in Fig. 1.2.2.

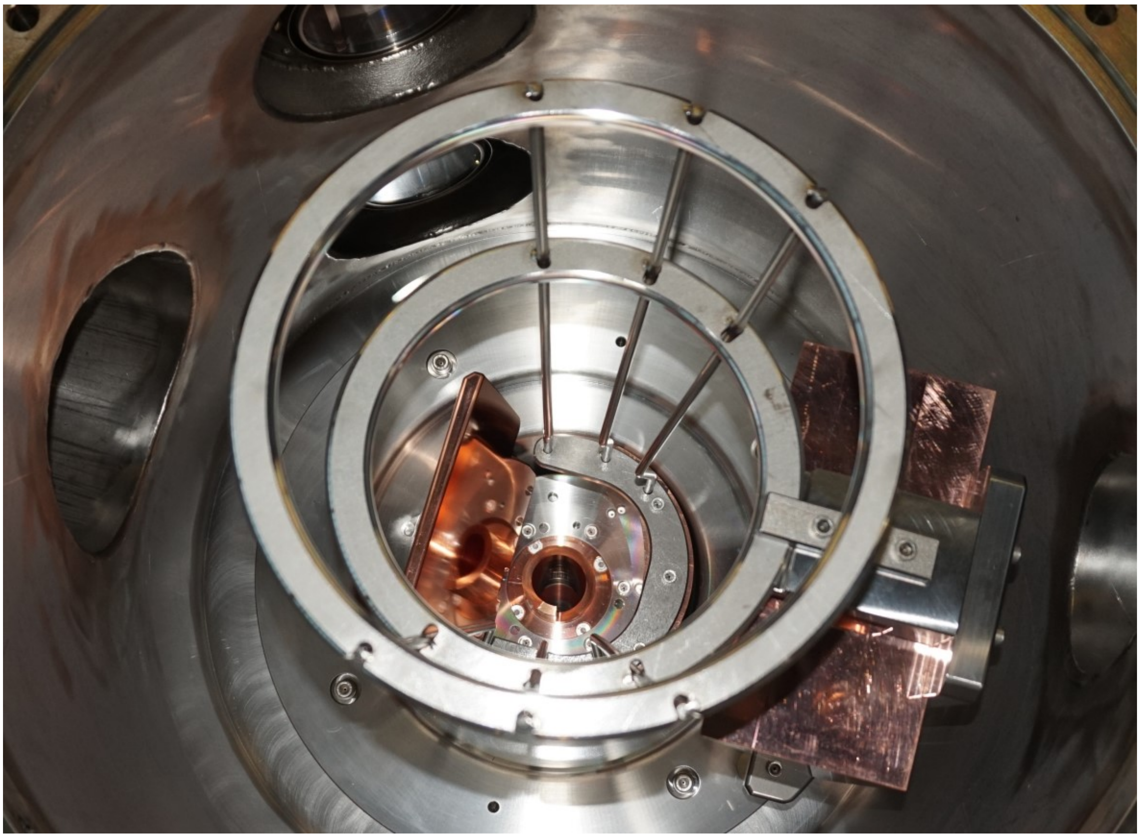


Fig. 1.2.1: Potential elevating structure

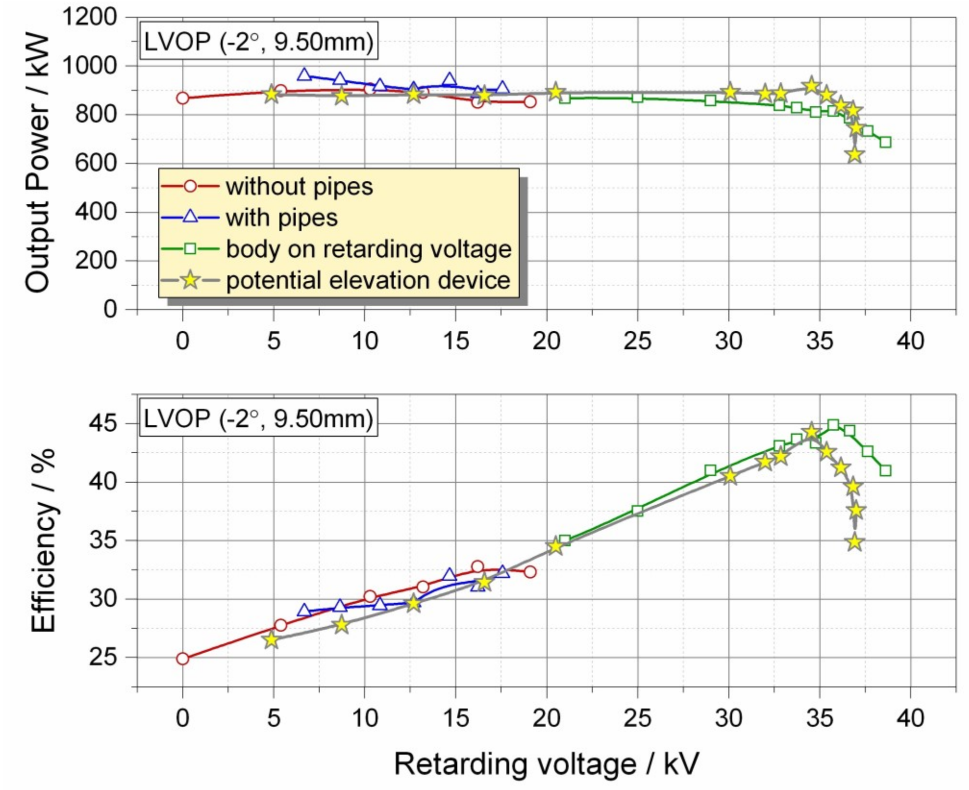


Fig. 1.2.2: RF power and total efficiency vs. retarding voltage obtained experimentally with different gyrotron configurations.

The beam tunnel is a critical part of the gyrotron, where unwanted parasitics oscillation can be excited having a negatively influence on the gyrotron performace. For this reason, very complicated and expensive constructions of beam tunnels consisting of ceramic damping structures are being used. Currently, the motivation is to build a simply-structured metallic alternative, more robust, less expensive and with comperable or even better dampig features. The first prototype of a fully metallic structure (Fig. 1.2.3) with an optimized inner wall contur has been tested with very encouraging results. During the tests, in a wide range of operating points, practically no parasitic signals were observed. Also an almost linear increase of the output power with respect to the beam current was demonstrated, which was not the case for gyrotron operation disturbed by the parasitic oscillation. Further tests of metallic beam tunel versions are ongoing.

Fig. 1.2.3: First prototype of fully metallic beam tunnel

1.3 Gyrotron Development for DEMO

Contact: K. 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. The current EU DEMO1 baseline 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. To this end, a longer-pulse 170 GHz, 2 MW coaxial cavity gyrotron is currently under development at KIT. This gyrotron is based on the short-pulse coaxial gyrotron, which was completely re-built, so that that all the key components i.e. beam tunnel, cavity, and quasi-optical system have independent cooling systems.

The goal of this upgrade is to be able to extend the pulse length up to 100 ms, provided that an axial sweeping system is used for the collector. For the verification of the manufacturing and the assembly of the new longer-pulse gyrotron, a short-pulse (ms) test campaign took place, using the old diode Magnetron Injection electron Gun (MIG) from the short-pulse tube. The verification was fully successful: after the conditioning phase and optimisation of the gyrotron operation parameters, the nominal cavity mode $TE_{34,19}$ was excited at 169.9 GHz with an output RF power close to 2.1 MW and an efficiency slightly above 30 % (in non-depressed collector operation). After further optimization of the magnetic field and by slightly increasing the beam current to 80 A, the RF output power reached nearly 2.2 MW, with an efficiency close to 33 % (in non-depressed collector operation). Due to known issues of the old electron gun and a relatively high body current value, the gyrotron was not operated in depressed collector operation. It is worthwhile to mention that the low-frequency parasitic oscillations (in the MHz range), which were usually observed in the previous prototypes of the coaxial gyrotrons, were not observed. In addition, high-frequency (>100 GHz) oscillations, which could be generated in the beam tunnel section, were also not found during the operation this tube. The tested gyrotron assembly as well as typical experimental results are shown in Fig. 1.3.1. After this experimental campaign, the old diode MIG was replaced with a new, advanced triode MIG with coated emitter edges, procured by Thales and compatible with long-pulse operation. Results on the first validation of this gun are reported in Section 1.4.

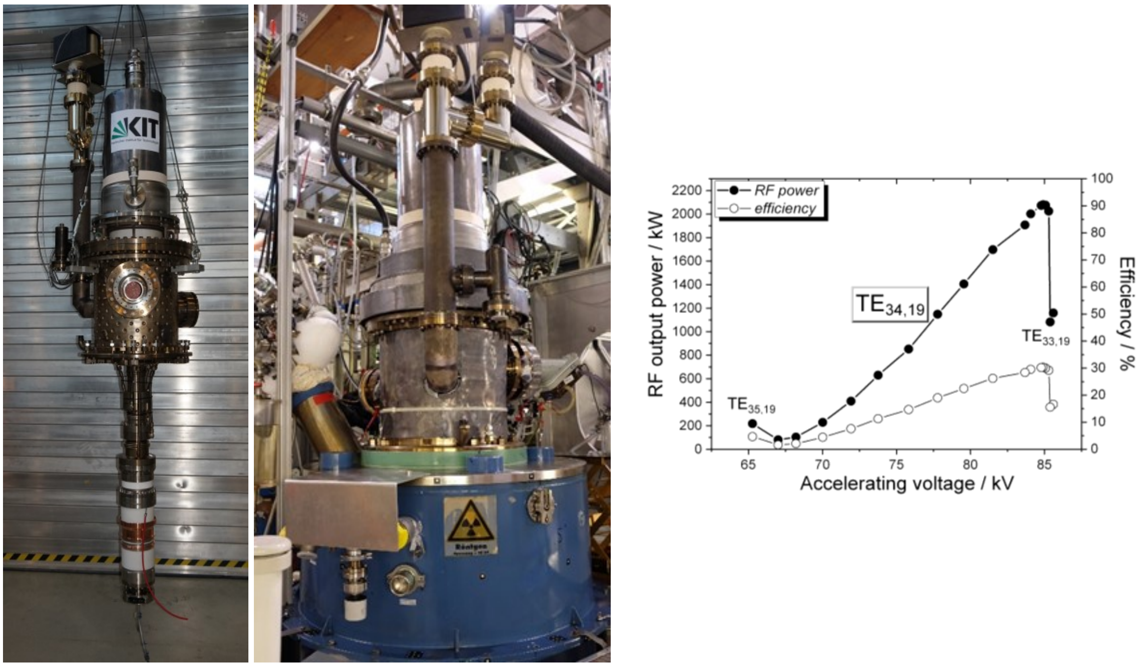


Fig. 1.3.1: left: longer-pulse coaxial gyrotron assembly with old diode gun before (left) and after (middle) installation in the superconducting magnet. Right: measured power and efficiency versus the applied accelerating voltage.

As the maximum acceptable heat-load on the cavity wall of fusion gyrotrons is a technological limiting factor for power, efficiency, and pulse-length, investigations on advanced cooling systems are ongoing. The thermal performance of a mini-channel cooling configuration has been numerically investigated using the ANSYS Fluent code-package. The influence of the various physical and operating parameters on the cavity cooling efficiency has been systematically studied for the 170 GHz, 2 MW coaxial-cavity gyrotron and an optimised heat sink design has been proposed. The pressure drop of the optimised heat sink design is 0.65 bar and the maximum cavity wall temperature reaches 261°C at steady state. The temperature of water remains below the boiling temperature. The temperature profile on the cavity wall and heat sink is presented in Fig. 1.3.2. Along with the numerical investigations, an in-house test set-up for the mini-channel cooling concept has been prepared (Fig. 1.3.3).

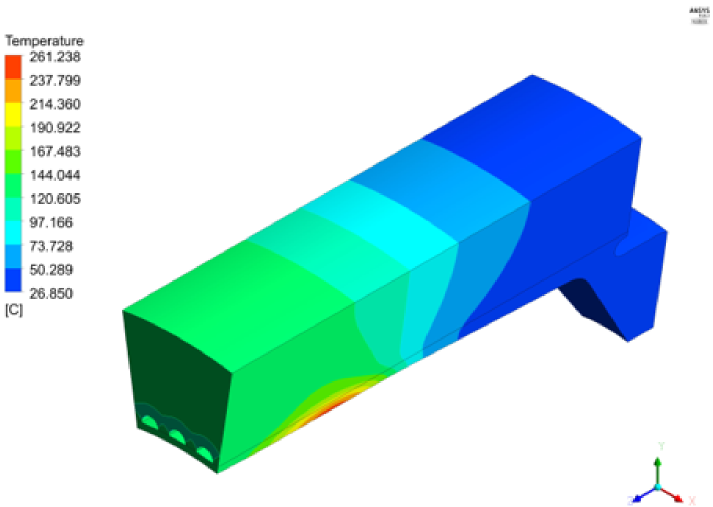


Fig. 1.3.2: Temperature profile on the cavity wall (18 degrees section) and heat sink with the proposed mini-channels.

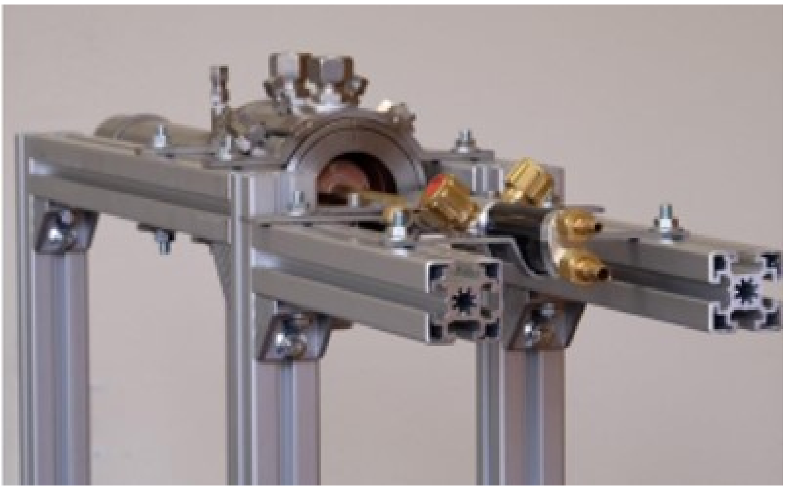


Fig. 1.3.3: Test set-up for the performance analysis of the mini-channel cooling concept.

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 is ongoing, using the existing 170 GHz, 2 MW coaxial gyrotron as a starting point. Operation at ~240 GHz is also under investigation. The chosen operating modes are $TE_{34,19}$, $TE_{40,23}$, and $TE_{48,26}$ at 170, 204, and 237 GHz, respectively. The modes at frequencies above 200 GHz can only be excited by the use of the new super-conducting 10.5 T magnet under procurement by TESLA Engineering Ltd (see Section 1.6). Therefore, in this period, the two existing triode coaxial electron guns, namely the MIG with coated emitter edges procured by Thales and the Inverse MIG (IMIG), manufactured at KIT, have been simulated using the magnetic field distribution of the new magnet to assess whether the required beam quality for proper operation can be achieved. The obtained results of the gun simulations using the in-house code-package ARIADNE, were used for the cavity interaction simulations performed with the code-package EURIDICE. With respect to dual-frequency 170/204 GHz operation, the interaction simulations show a generated RF output power of 2.6/2.1 MW and an interaction efficiency of 38.3/34.2 % at 170/204 GHz, respectively. The values are determined in accordance to the gyrotron development constraints, where the cavity wall loading is limited to 2 kW/cm^2. The results are summarised in Table 1.3.1. A typical start-up scenario is shown in Fig. 1.3.4.

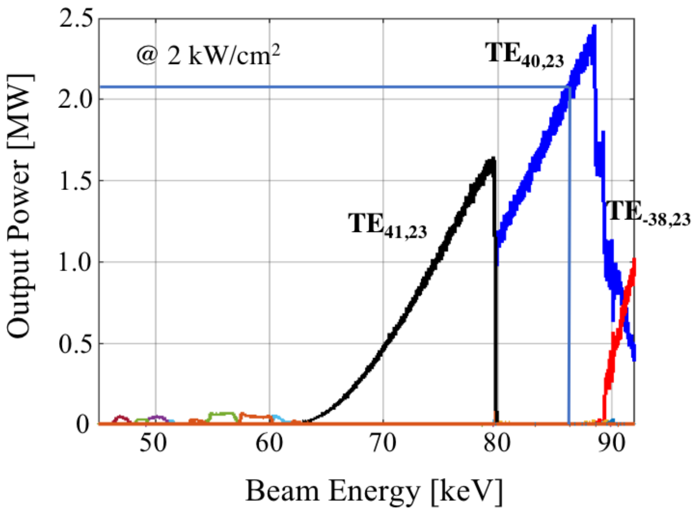


Fig. 1.3.4. Start-up scenario at 8.23 T and I = 68 A using the magnetic field distribution of the upcoming 10.5 T magnet and the IMIG at a nominal beam energy of 86.4 keV.

	MIG with coated emitter		Inverse MIG	
Frequency [GHz]	170.00	204.15	170.00	204.15
Mode	$TE_{34,19}$	$TE_{40,23}$	$TE_{34,19}$	$TE_{40,23}$
RF Power [MW]	2.60	2.08	2.57	2.08
Interaction Efficiency [%]	38.3	34.2	38.0	33.8
Beam energy [keV]	91.5	87.5	91.5	87.5
Beam current [A]	75	68	75	68
Magnetic field [T]	6.86	8.23	6.86	8.23

Table 1.3.1: Results of interaction simulations with EURIDICE in the gyrotron cavity and non-linear up-taper, assuming realistic magnetic field profile and electron beam properties obtained by ARIADNE.

A quasi-optical mode converter has been designed for an dual-frequency coaxial-cavity gyrotron, which is operated in the $TE_{34,19}$ mode at 170 GHz and the $TE_{40,23}$ mode at 204 GHz. A mirror-launcher has been designed for the dual-frequency coaxial-cavity gyrotron. The simulation results show that the Gaussian-mode contents at the launcher aperture are 97.17% and 96.58% when the launcher operated in the $TE_{34,19}$ mode at 170 GHz and in the $TE_{40,23}$ mode at 204 GHz, respectively. The field distributions are shown in Fig. 1.3.5.

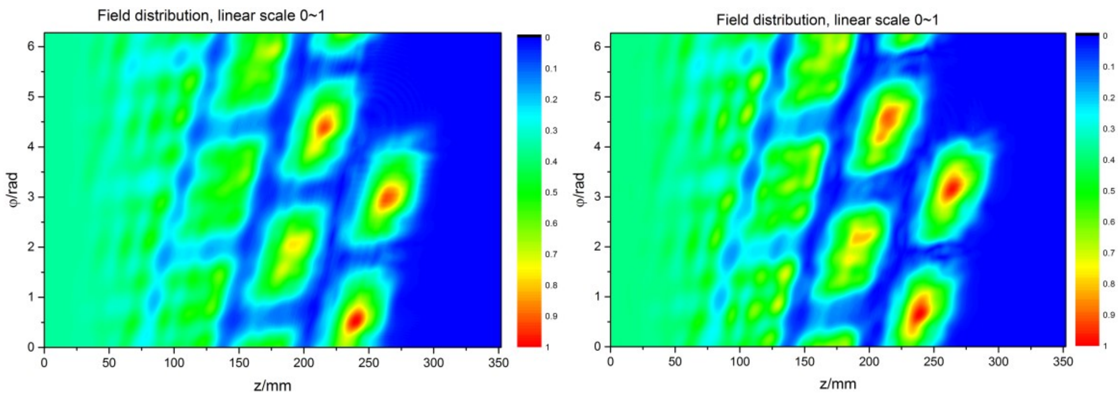


Fig. 1.3.5: Field distribution on the launcher wall (linear scale 0~1): operating in the $TE_{34,19}$ mode at 170 GHz (left) and in the $TE_{40,23}$ mode at 204 GHz (right).

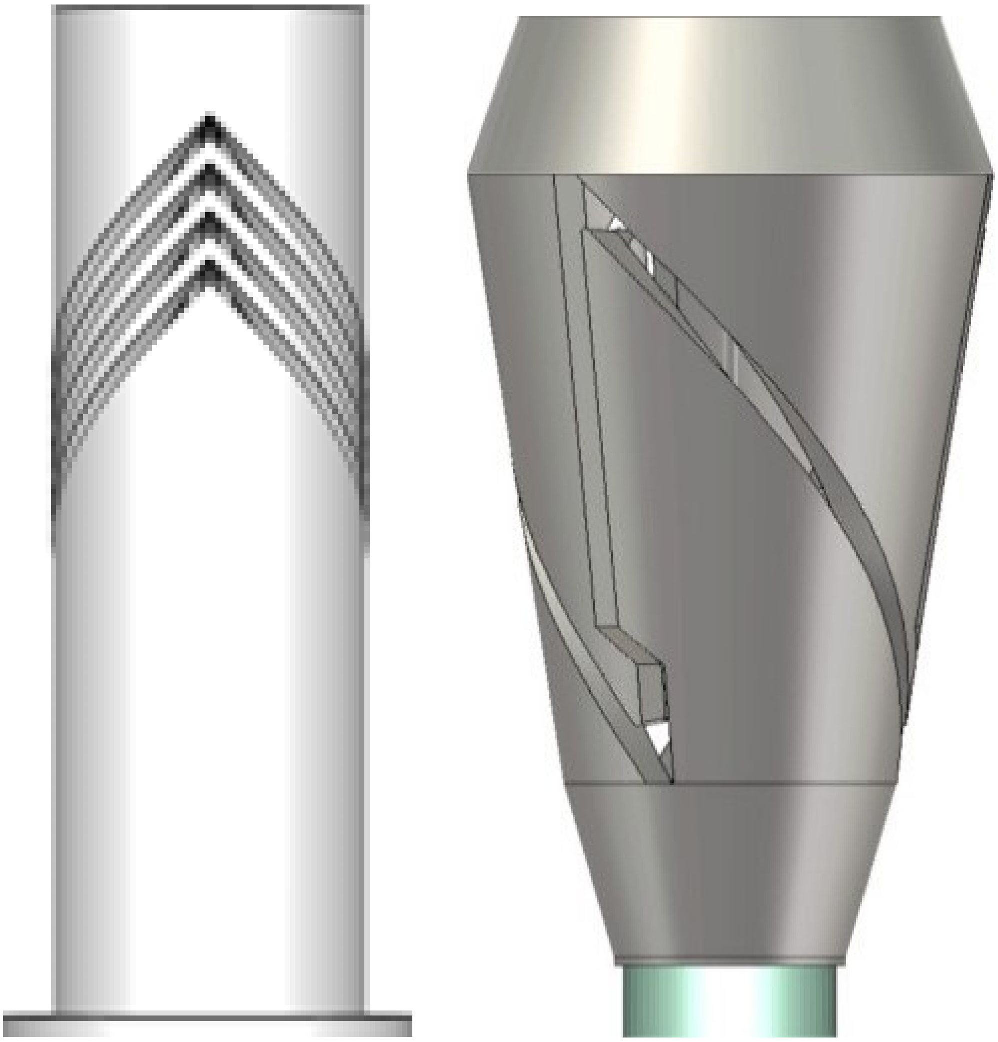


Fig. 1.3.6: A coaxial four stages MDC at (left) and a cylindrical two stages MDC (right).

A mirror system is currently being developed for the dual-frequency gyrotron.

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. The challenge for the design of a successful MDC system for a high power gyrotron is the sorting of the magnetically confined electrons of the spent beam on the electrodes, according to their kinetic energy. The **E**×**B** drift is considered as a very promising concept for this purpose, as was proposed by Pagonakis *et al*. in 2008. A coaxial and a cylindrical design approach (see Fig. 1.3.6) based on the configuration of an azimuthal electric field using helical electrodes have been extensively investigated. A preliminary conceptual design of an **E**×**B** drift MDC system for gyrotrons is ongoing (Fig. 1.3.7) for the validation of the principle in a short-pulse, high-frequency, high-power gyrotron. The construction and testing are planned in the near future.

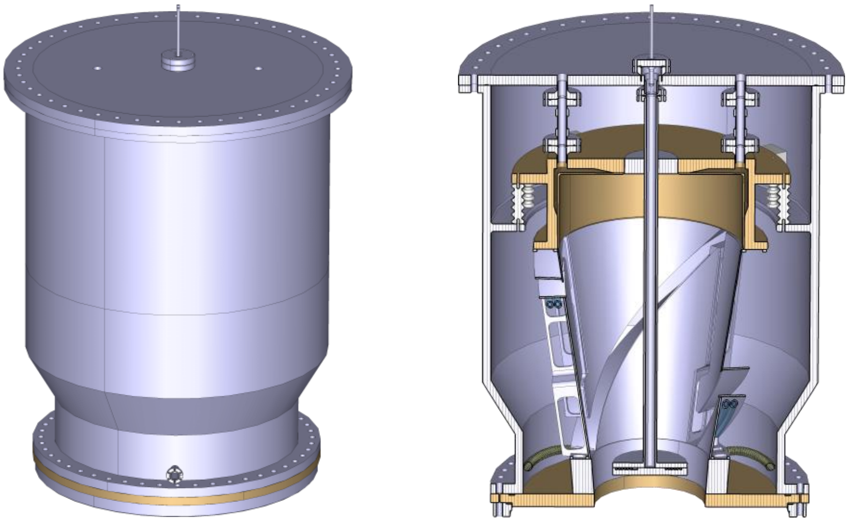


Fig. 1.3.7: Drawings of the preliminary conceptual design of a two-stage E×B MDC.

The consideration of frequency step-tunability of the DEMO gyrotron is related to the required option to fine-tune, by changing the gyrotron frequency, the deposition location of the microwave energy into the plasma, in order to support plasma instability control. In particular, the Electron Cyclotron (EC) system can deposit microwave power localised in the space near the intersection of the microwave beam and the electron cyclotron resonance. Therefore, one important application of EC is to locally drive current at the modes of MHD instabilities, which are localized near rational magnetic flux surfaces in tokamaks. This requires a quasi-continuous steering of the absorption (resonance) location over a certain range of flux surfaces. The steering of the absorption can be achieved by changing the launching angle of the microwave beam, or by tuning the frequency of the microwaves. The latter is based on the fact that the frequency of the EC resonance is proportional to the magnetic field. Since there is a gradient of magnetic field in the tokamak, the position of the EC resonance shifts as the microwave frequency varies, and this is the so-called frequency steering, as illustrated in Fig. 1.3.8.

The principle of this steering mechanism is not new, but the feasibility of the frequency steering for EU DEMO has not been extensively studied up to now. A comprehensive investigation has now been initiated in the frame of a EUROfusion Engineering Grant, which involves the study of the current-drive performance and the engineering feasibility of frequency steering, with respect to the transmission system, the windows, and the gyrotrons. The work is being performed in collaboration primarily with CNR, Italy and IPP.

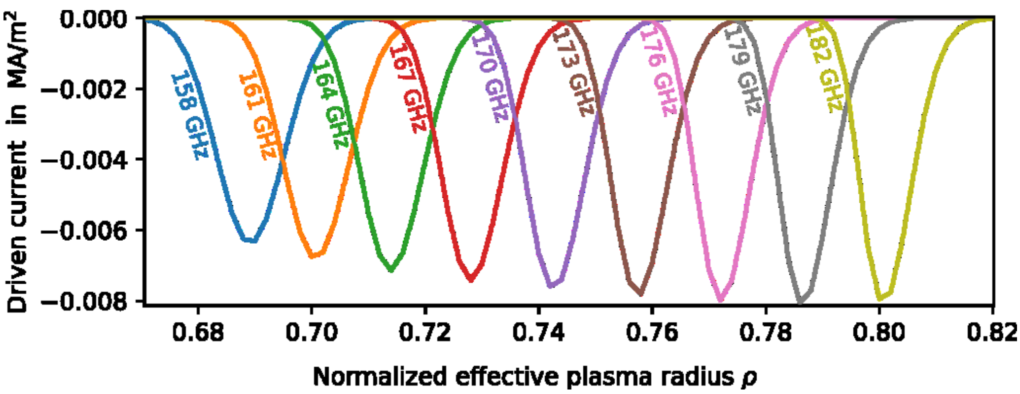


Fig. 1.3.8: Illustration of a first simulation of the localized current drive from the equatorial port of EU DEMO achieved at different frequencies.

1.4 Advanced electron gun design for gyrotrons

Contact: Dr. Ioannis Pagonakis

An improved magnetron injection gun (MIG) for application in the coaxial cavity gyrotron has been designed at KIT and manufactured by the industrial partner Thales Electron Devices (TED).

The new MIG has several novelties, such as: (i) the design satisfies the criteria for the suppression of the electron trapping mechanisms, (ii) a new type of emitter ring is used for the suppression of the influence of the manufacturing tolerances and misalignments on the quality of the generated electron beam (see Fig. 1.4.1), and (iii) the design was optimized to generate good beam quality in a wide variety of magnetic field profiles to increase the flexibility.

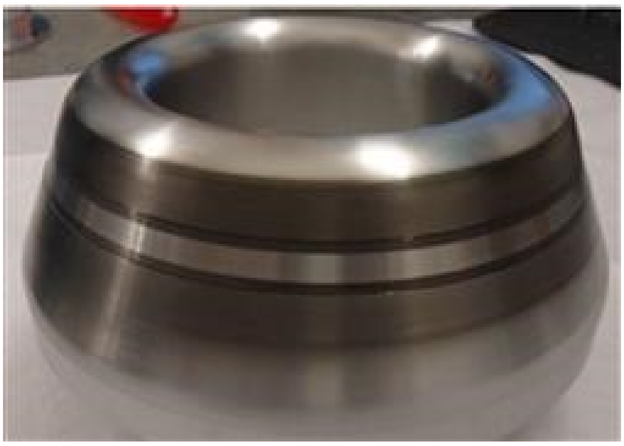


Fig. 1.4.1: New MIG for coaxial cavity gyrotron with anti-emissive coating of the emitter.

Preliminary experiments were performed with promising results. The triode operation of the gun was shortly investigated and a power in the range of 2 MW was measured as shown in Fig. 1.4.2.

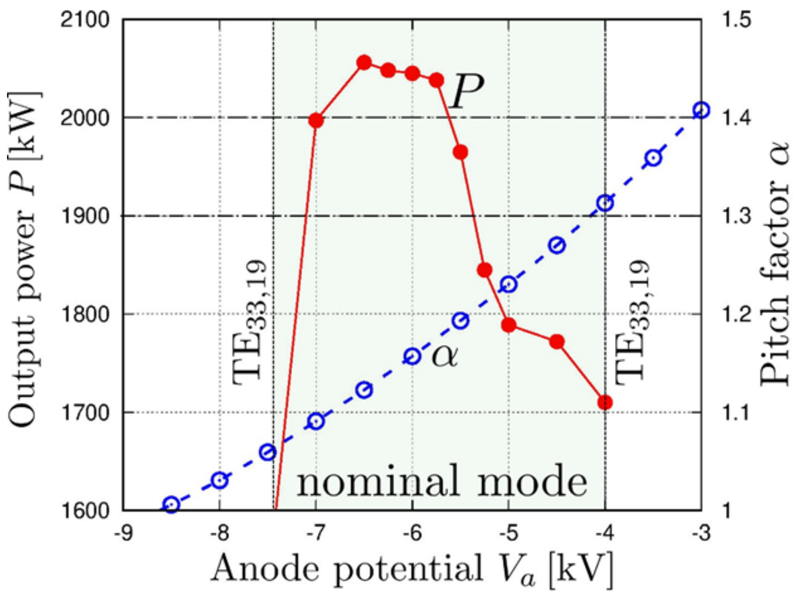


Fig. 1.4.2: Experimental measured output power P and theoretical pitch factor α as functions of the modulation anode potential.

1.5 Developments on theory and numerical simulations

Contact: Dr. Stefan Illy

The simulation model of gyrotron interaction has been extended to investigate the possibility of parasitic After-Cavity Interaction (ACI) in the gyrotron launcher. In contrast to previous works, the extended simulation model allows, for the first time, to consider a very large interaction region (i.e. cavity, uptaper, and launcher) using accurate electromagnetic field representation not only in the cavity and uptaper, but also in the launcher. In particular, the code-package EURIDICE for gyrotron interaction simulations and cavity design has been upgraded to address also the coupled TE modes which form the electromagnetic field in the launcher. An interface has been developed, in order to import to EURIDICE the launcher electromagnetic field as obtained by the code KarLESSS. Using the newly developed model, the 1 MW, 140 GHz gyrotron for W7-X, the 1 MW, 170 GHz European gyrotron for ITER, and the 170 GHz, 2 MW coaxial-cavity gyrotron at KIT, have been studied. As it turned out, parasitic ACI in the launcher is possible in several cases, resulting in a reduction of gyrotron efficiency. An example of such a case is given in Fig. 1.5.1. The extended model provides additional means to possibly remove previously observed discrepancies between gyrotron simulations and experimental results.

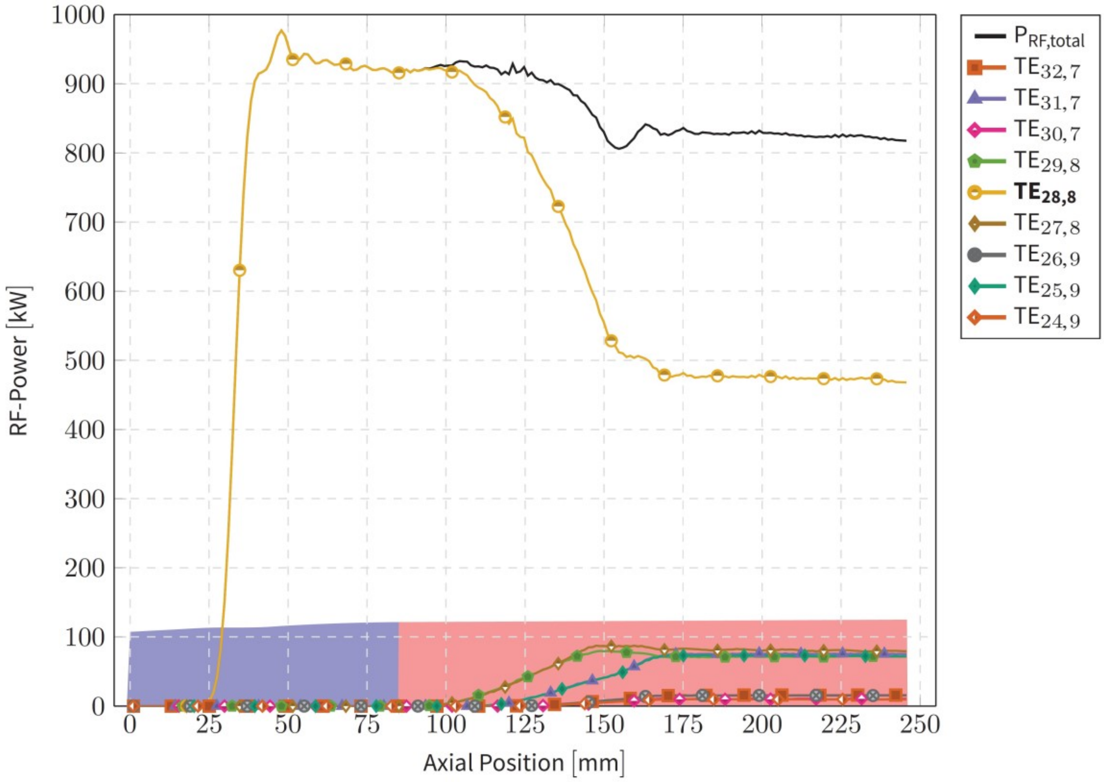


Fig. 1.5.1: Example of ACI in the launcher that can occur in the 140 GHz, 1 MW gyrotron for W7-X. Cavity and uptaper extend up to 85 mm (purple region); launcher up to 245 mm (red region). Black line shows total RF power versus the gyrotron axis; coloured lines show power of individual modes, as the operating $TE_{28,8}$ mode is converted in the launcher to a mixture of 9 modes, in order to achieve a Gaussian RF field profile. A reduction of ~100 kW due to ACI in the launcher is visible in the total RF power.

1.6 FULGOR (Fusion Long-Pulse Gyrotron Laboratory)

Contact: Dr. Gerd Gantenbein

The existing gyrotron test facility at KIT, which had been designed and built about 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)

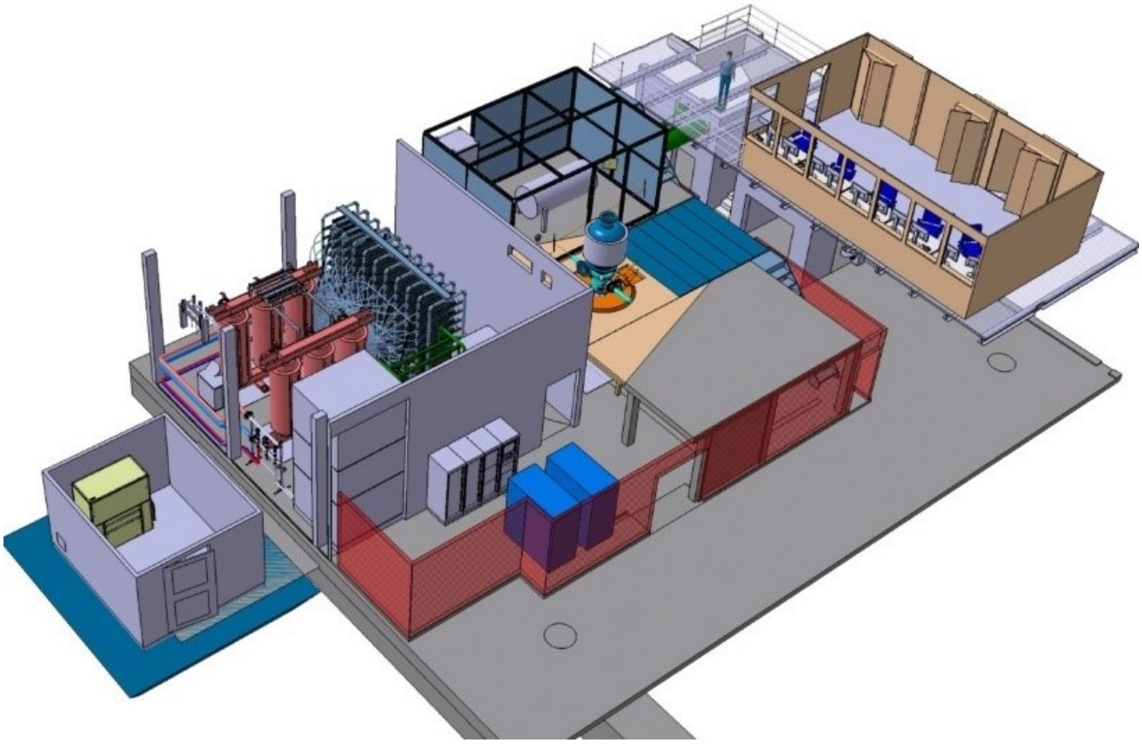
The high voltage power supply (HVPS) will support an operating voltage of up to 130 kV with up to 120 A beam current in short pulse operation and 90 kV / 120 A in continues wave regime. A superconducting magnet which allows operation of gyrotrons at frequencies well above 200 GHz will be a major component of FULGOR. 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. 1.6.1 is 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): In 2018 the final acceptance tests of the CW power supply and the pulsed PS has been performed. The procurement of components and the production of the body power supply has been started and is ongoing.

Superconducting magnet: This is a very challenging component since the requirements are beyond what is industrial standard. In particular, a large borehole diameter (261 mm) in combination with a high magnetic field requirement (up to 10.5 T to ensure RF radiation up to 240 GHz) calls for a very clever design of the magnet. In 2018 the procurement has been placed at TESLA company, GB, manufacturing of major parts has started and the delivery of the magnet to KIT is expected in summer 2019.



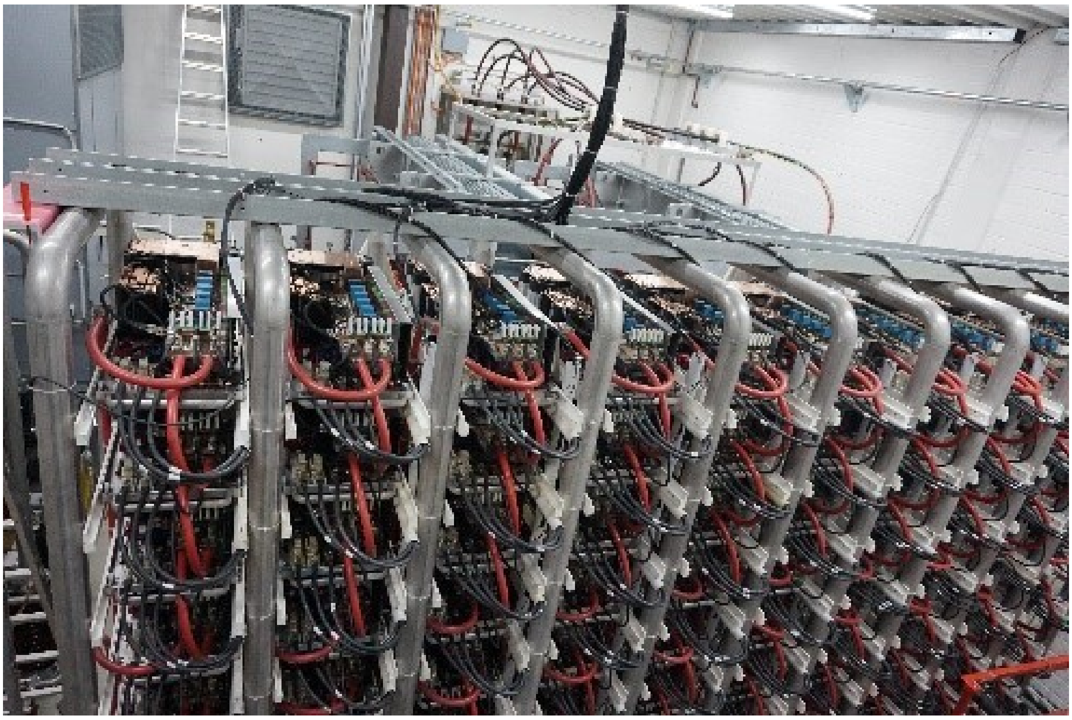


Fig. 1.6.1: CAD view of FULGOR teststand and installation of CW modules.

1.7 Generation of ultrashort pulses with new gyro-devices

Contact: M.Sc. Alexander Marek

In this project, we study the generation of a periodic sequence of powerful short pulses. 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, as 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. For prove of concept, such a feedback loop should be first realized at a frequency of 34 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 34 GHz. In the 34 GHz system, a gyrotron-traveling-wave-tube with helical corrugated interaction-region (helical gyro-TWT) will be used as amplifier device, while a rectilinear electron beam in a cylindrical interaction space will be used as cyclotron absorber. In the final 260 GHz generator, an absorber based on a helical gyro-TWT operating in the Kompfner-Dip regime should be used as absorber device. The Kompfner-Dip absorber has the advantage of a halved magnetic field compared to the cylindrical absorber (10 T → 5 T). The amplifier (helical gyro-TWT) will run in a regime optimal for the maximal amplification of ultra-short pulses, while the absorber will run in a regime, where low-energy pulses are absorbed and powerful pulses can pass the absorber without loss of energy.

“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, Ma18]. 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 34 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.

For the amplifier as well as the absorber devices of a final 260 GHz pulsed generator, a broad-band CUSP-type electron gun was designed (see Fig. 1.7.1). The gun allows the generation of high quality small-orbit electron beams, as required for helical gyro-TWTs. The designed gun can be used for helical gyro-TWTs operating at various frequencies, from the W-band up to the J-band. For the development of the gun the in-house tools Ariadne and ESRAY were used. In addition, for the first time a cross-check and investigation of unwanted mode-excitation were performed with the commercial software CST-MICROWAVE-STUDIO.

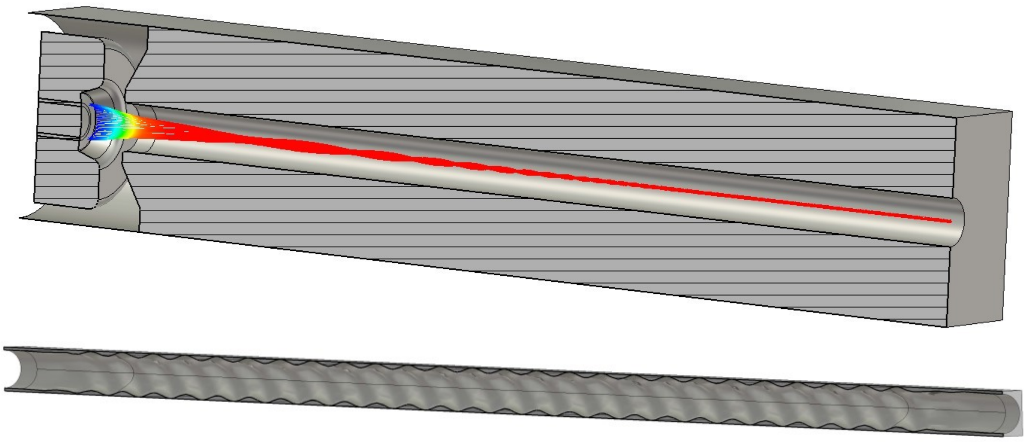


Fig. 1.7.1: CUSP-type electron gun with beam tunnel, to be attached to a helical gyro-TWT (top). Cross-section of a helical waveguide structure for a helical gyro-TWT (bottom).

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.

1.8 Gyrotron Diagnostics

1.8.1 A diagnostic device for the study of Magnetron Injection Guns used in high-power, high-frequency gyrotrons.

Contact: Dr. Zisis Ioannidis

The quality of the electron beam generated by a Magnetron Injection Gun (MIG) is very important for the performance of high-power, high-frequency gyrotrons. In practice, several parameters such as mechanical misalignments during assembly, manufacturing tolerances, temperature inhomogeneity and emitter roughness, significantly affect the expected performance of the MIG. For this reason, it is important to be able to measure the electron properties. During gyrotron operation, that kind of measurement is practically impossible. A more reasonable approach is to develop a diagnostic device based on the retarding field method, where the MIG can be connected and studied prior the gyrotron operation.

Fig. 1.8.1 presents the prototype device that was manufactured at KIT after detailed simulation studies. The operating principle of the diagnostic device is quite simple. The device is installed in the superconducting magnet that is used for the gyrotron operation. The generated electron beam of the MIG under study is accelerated by the anode-cathode potential difference and is guided towards the position where the gyrotron interaction region would be by a focusing magnetic field. A diaphragm with a small opening is intercepting the electron beam, allowing only to a specific azimuthal sample of the beam to pass through and enter the retarding field that is created between the diaphragm and the reflector. Depending on the applied retarding potential and the parallel energy of the electrons, some electrons are reflected backwards, whereas those that have enough parallel energy to overcome the retarding forces of the reflector are finally collected by the collector.

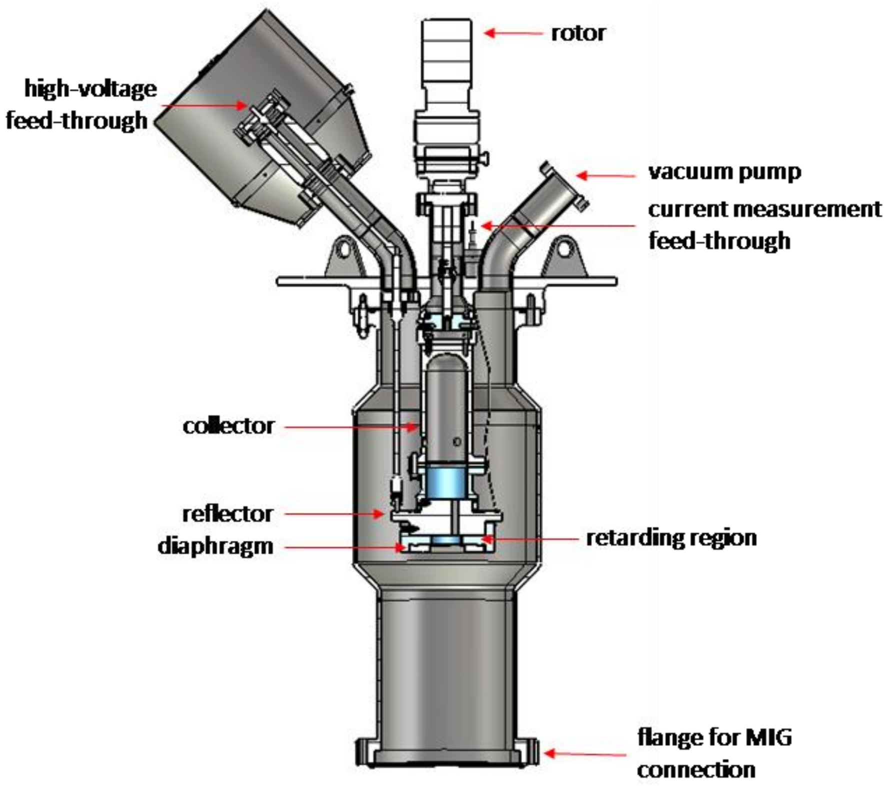


Fig. 1.8.1: Representation of the prototype diagnostic device that was manufactured for the study of the beam quality of magnetron injection guns.

Various useful measurements can be made with such a device. First, it is possible to measure the azimuthal homogeneity of the emission by grounding the reflector, rotating the diaphragm and measuring the collector current with respect to the azimuthal position of the diaphragm's slot. Second, for a specific position of the diaphragm, it is straightforward to measure the parallel energy distribution of the electrons by varying the reflector potential and measuring the collector current. Then, it is also possible to estimate the complete pitch factor distribution of the electrons. Finally, by changing the magnetic field profile and measuring the collector current it is possible to estimate the beam thickness. Experiments with MIGs that have been operated in the past with the 2 MW, 170 GHz short-pulse prototype gyrotron are currently ongoing. Further tests with other MIGs are planned for the future.

1.8.2 Experimental study on further performance optimization of the European 1 MW, 170 GHz Hollow-Cavity Gyrotron Prototype.

Contact: M.Sc. Tobias Ruess

The quasi-optical mode converter is one key element in the gyrotron design, which consists of the launcher and three mirrors. Those components convert the high-order rotating waveguide mode, excited in the interaction cavity, into the linearly polarized fundamental Gaussian beam (TEM00 mode). In order to perform a proper verification of the quasi-optical system a low power (~ 1 mW – cold test) measurement of this converter system is vital before final installation into the high power fusion gyrotron. The first step of validation of the quasi-optical mode converter is the excitation of the correct high-order TEm,n-mode with a mode generator. In the past, this mode generator was adjusted manually which was a very time consuming task because of the high spectral density of the mode spectrum in oversized waveguides, as well as the large number of degrees of freedom of the mode generator setup. To imprive this procedure two high-precision linear drivers (horizontal and vertical movement) are installed. Using this electronical adjustable components, the mode generator setup was automated. Mode evaluation algorithms have been implemented to determine the mode indices and the mode purity. The mode generator setup is shown in Fig. 1.8.2. The mode generator is operated with a VNA (Vector Network Analyzer), covering a frequency range from 140-330 GHz using extension modules and a rectangular standard waveguide pick-up receiving antenna. This antenna is mounted on a 3D measurement arm, where a stepwise 2D scan of the plane parallel to the output of the mode generator can be taken. The amplitude pattern of the TE28,8-mode operating at 140.006 GHz is depicted in Fig. 1.8.3. The scalar mode content is calculated to 94.5 % with a extremly low counter-rotating amount of around 0.33 %. The complete quasi-optical system (launcher and mirrors) are tested after the successful excitation of the mode. This measuremt delivers a scalar/vectorial Gaussian mode contet of 98.3/97.5 %.

With these improvements the precision of the measurement has been increased and the measurement time has been decreased substantially.

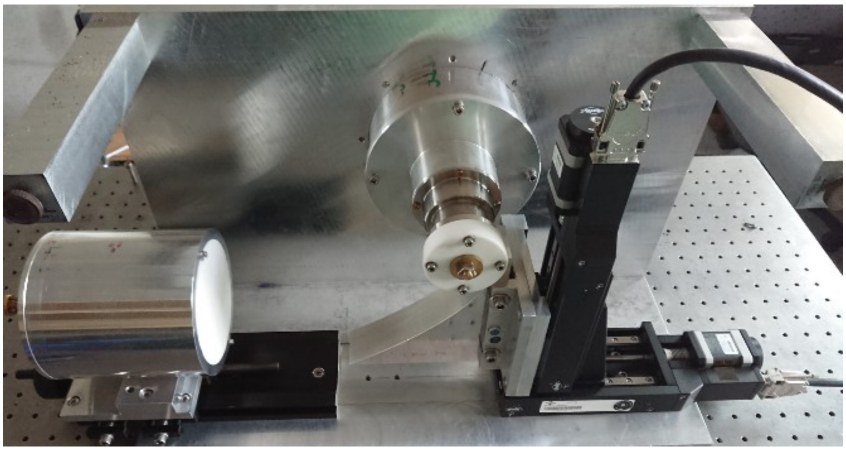


Fig. 1.8.2: Photo of the the automated mode generator setup.

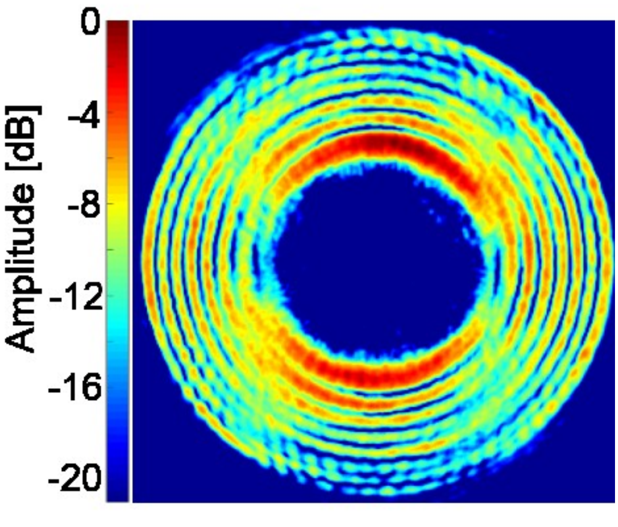


Fig. 1.8.3: Measured amplitude pattern of the $TE_{28,8}$ mode operating at 140.006 GHz with a pixel size of 0.2x0.2 mm.

Involved Staff:

KIT/IHM: K. Avramidis, B. Ell, **Dr. G. Gantenbein, Dr. S. Illy**, Dr. Z. Ioannidis, Prof. J. Jelonnek, Dr. J. Jin, Dr. P. Kalaria, Th. Kobarg, R. Lang, W. Leonhardt, A. Marek, M. Marschall, D. Mellein, Meier (KIT, IAM-AWP), Dr. I. Pagonakis, A. Papenfuß, S. Ruess (KIT CS), T. Ruess, **Dr. T. Rzesnicki**, Prof. Dr. Theo A. Scherer (KIT, IAM-AWP), M. Schmid, Dr. D. Strauss (KIT, IAW-AWP), Prof. M. Thumm, S. Wadle, J. Weggen, Dr. Ch. Wu, A. Zein, **IGVP (University of Stuttgart): Dr. W. Kasparek**, Dr. C. Lechte, Dr. B. Plaum, F. Remppel, H. Röhlinger, B. Roth, S. Wolf, A. Zeitler, **IPP (Greifswald/Garching):** B. Berndt, Dr. H. Braune, F. Hollmann, L. Jonitz, **Dr. H. Laqua**, Dr. S. Marsen, F. Noke, M. Preynas, F. Purps, A. Reintrog, T. Schulz, T. Stange, P. Uhren, M. Weißgerber, F. Wilde

Journal Publications

W7-X Team; Dinklage, A.; Beidler, C. D.; Helander, P.; Fuchert, G.; Maaßberg, H.; Rahbarnia, K.; Sunn Pedersen, T.; Turkin, Y.; Wolf, R. C.; Alonso, A.; Andreeva, T.; Blackwell, B.; Bozhenkov, S.; Buttenschön, B.; Czarnecka, A.; Effenberg, F.; Feng, Y.; Geiger, J.; Hirsch, M.; Höfel, U.; Jakubowski, M.; Klinger, T.; Knauer, J.; Kocsis, G.; Krämer-Flecken, A.; Kubkowska, M.; Langenberg, A.; Laqua, H. P.; Marushchenko, N.; Mollén, A.; Neuner, U.; Niemann, H.; Pasch, E.; Pablant, N.; Rudischhauser, L.; Smith, H. M.; Schmitz, O.; Stange, T.; Szepesi, T.; Weir, G.; Windisch, T.; Wurden, G. A.; Zhang, D.; Baumann, K.; Dammertz, G.; Fietz, W. H.; Gantenbein, G.; Huber, M.; Hunger, H.; Illy, S.; Jelonnek, J.; Kobarg, T.; Lang, R.; Leonhardt, W.; Losert, M.; Meier, A.; Mellein, D.; Papenfuß, D.; Samartsev, A.; Scherer, T.; Schlaich, A.; Spiess, W.; Thumm, M.; Wadle, S. (2018). Magnetic configuration effects on the Wendelstein 7-X stellarator. Nature physics, 14 (10), 1067.

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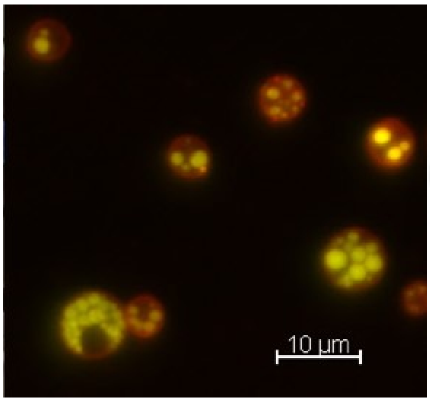
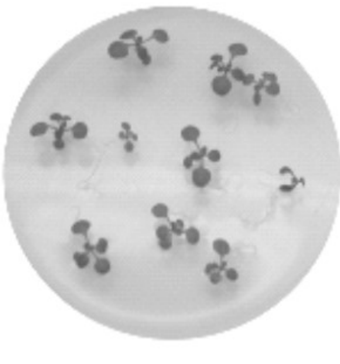
2 Renewable Energy (RE): Bioenergy-Feedstocks and Pretreatment-

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 PEF-Processing of Microalgae and Industrial Water Streams

Contact: Wolfgang Frey

2.1.1 DiWal

Legal restrictions on solvent and bactericide admixture to water-based paint systems in electrocoating lines for car bodies improve environmental sustainability of these large scale industrial processes, but also favour growing conditions for unwanted bacterial populations. Bacterial inactivation by PEF treatment is being tested for feasibility in this project.

First condition for a successful application of PEF-technique for bacterial decontamination of water-based paint media is that dip coat paint will not be deposited at the electrodes' surface in the PEF treatment chamber, which finally would result in blocking of the treatment chamber. Pilot experiments revealed that paint deposition can be inhibited by utilization of short pulses with a duration between 0.75 µs and 2°µs. Longer pulses were found to cause paint coagulation and paint deposition at the electrodes.

In collaboration with the Institue of Functional Interfaces, *Burkholderia*, *Sphingomonas* and *Microbacterium* were identified as main contaminants in electrocoating lines. Inactivation efficiency was tested on isolated strains for inactivation efficiency of PEF-treatment with 1 µs and 2 µs long pulses.

It can be ascertained that inactivation is highest, when a treatment energy of 80 kJ/l was applied. Reduction of the treatment energy to 40 kJ/l reduces inactivation rate by 0.5 log on average. Inactivation performance does not primarily depend on pulse duration. In all cases, bacterial inactivation rate exceeded the required value of 2 log, Fig. 2.1.1, dashed line. Both results, sufficient inactivation performance at low energy input and paint-deposition-free operation of PEF-treatment chambers are important prerequisites for successful implementation of the PEF-technology in electrocoating lines.

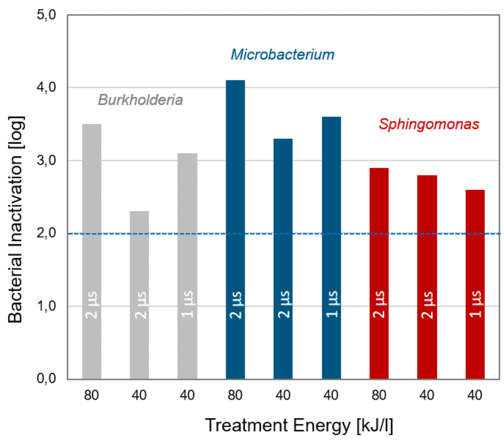


Fig. 2.1.1: Inactivation of bacteria isolated from electrocoating lines by PEF-treatment with 1 µs and 2 µs long pulses at a specific treatment energy of 40 kJ/l and 80 kJ/l.

Collaboration: Eisenmann SE, Hochschule Pforzheim, BMW Group, PPG, FreiLacke

Funding: Federal Ministry of Education and Research – BMBF, Grant No. 02WAV1405A

2.1.2 SABANA

Efficient product recovery from microalgae is impeded by the organisms' robust cell walls. Thus, extraction of intracellular components from microalgae requires a pretreatment step for cell disruption. A major task in the H2020 SABANA project is to identify an economic downstream processing pathway, involving appropriate cell disruption techniques, for the production of amino acid concentrates utilized as fertilizer in agriculture and horticulture. A first screening of various pretreatment methods for cell disruption, i.e. enzymatic cell wall digestion, ultrasound application, thermal pretreatment, ball milling, etc. revealed that PEF-processing and high pressure homogenization (HPH) are the most economic candidates. Both methods provide high product yields at low energy expenses of 1 MJ/kg_{dw} and less.

For pilot-scale onsite tests of the cell disruption efficiency of PEF treatment a 3 l/h pilot facility was manufactured. It consists of a 15 element pulse forming network generator, a continuous flow treatment chamber and pumping auxillaries. The generator provides 1.5 µs long rectangular pulses of an amplitude of 25 kV. At an electrode distance of d = 0.6 cm the maximum electric field in the treatment chamber amounts to E = 41.6 kV/cm, a value which was proven for high efficiency in previous lab-scale trials.

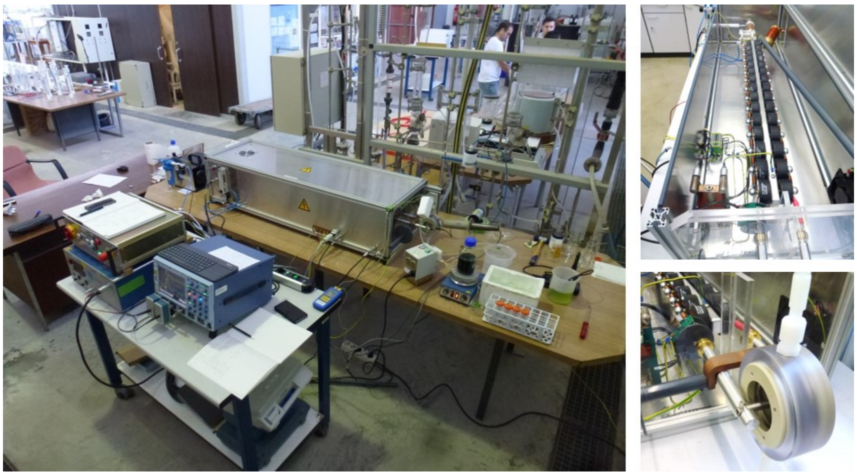


Fig. 2.1.2: Pulse Forming Network generator for pilot-scale PEF-processing of microalgae installed at the University of Almería for on-site experiments. Overall view of the installation, left. View into the generator housing onto the 15 element pulse forming network generator in Blumlein configuration, right, upper image. The treatment chamber, mounted at the generators interface consists of a polycarbonate housing and two parallel stainless steel electrodes, right, lower image.

Two joint experimental campaigns were conducted at the University of Almería in 2018. It could be demonstrated that PEF-treatment and HPH pretreatment prior to emzymatic hydrolysis result in comparable amino acid yields of 60% in maximum at treatment energy expenses of 1 MJ/kg_{dw}. Energy efficiency of HPH-treatment does not depend on media conductivity as it is the case for PEF-treatment, which is a processing advantage of HPH if marine strain have to be processed. On the other hand, since PEF-treatment preserves cell shape and biomass separability, it allows recovery of the aqueous fraction prior to the enzymatic hydrolysis step for amino acid concentrate production from freshwater species. The water soluble, first fraction contains growth stimulative substances and natural pesticides, which additionally could be marketed if PEF-pretreatment would be selected for preferential cell disruption technology in this project.

Collaboration: University of Almería, GEA Westfalia, Biorizon

Funding: H2020, SABANA, Grant Agreement No. 727874

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, which are operated in triggered mode. If the generators’ charging voltage reaches a predefined level, a trigger signal is generated causing immediate triggering of both generators. Thereby, triggering is performed by applying an over-voltage to the first spark gap of each generator. Hence, an additional trigger electrode has been omitted. The triggered operation enables charging of both generators from a single high-voltage power supply.

Fig. 2.2.1 shows the well synchronized pulse currents of both generators after triggering.

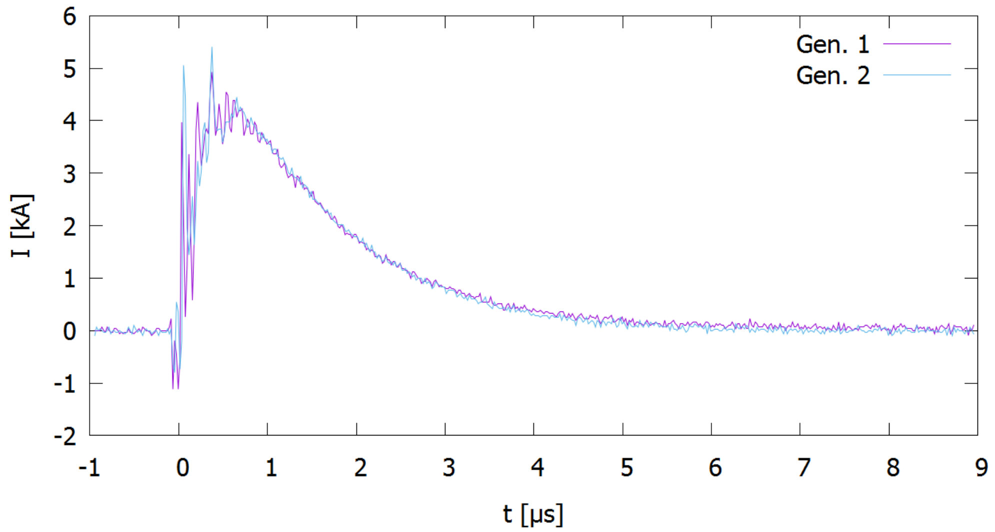


Fig. 2.2.1: Measured pulse currents of both generators.

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.

ZIM Zentrales Innovationsprogramm Mittelstand

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

A 149-stage pulse generator for stepwise arbitrary waveform generation to drive the Pulsed Electron Beam Device (GESA) has been set up and is currently being tested. Fig. 2.2.2 shows photos of the generator. The generator has been designed for an output voltage of 120 kV and a load current of up to 600 A. The generator features a helical stage arrangement with a quasi-coaxial current return path. 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. During pulse generation the stage capacitors of active stages are continuously discharged causing a droop of the output voltage. Stepwise arbitrary waveform generation allows for an active droop compensation. Thereby, an additional stage is activated as soon as the output voltage drops by an amount equal to the stage voltage. Fig. 2.2.3shows the output voltage of the generator with active droop compensation in red in comparison to the the decreasing voltage shape without droop compensation (black).

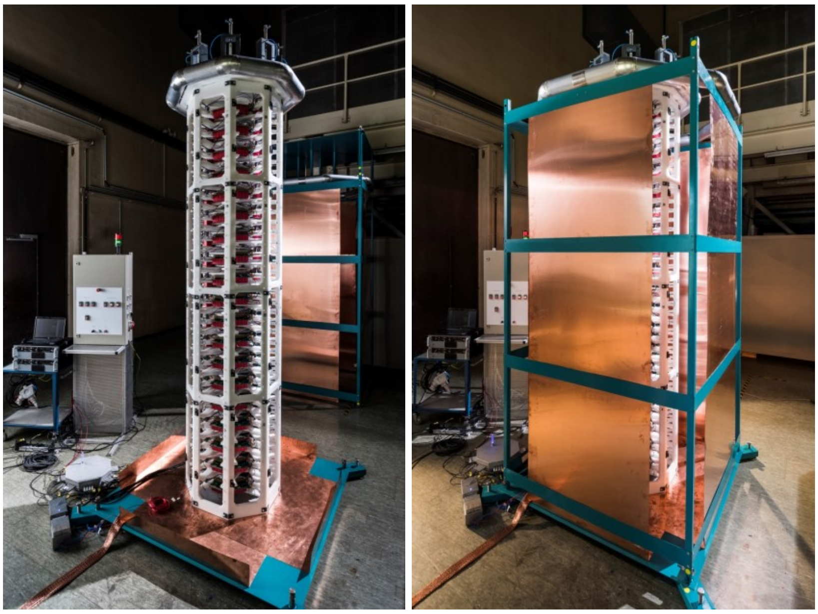


Fig. 2.2.2: 9-stage pulse generator for arbitrary waveform generation without current return path (left) and with attached current return path (right).

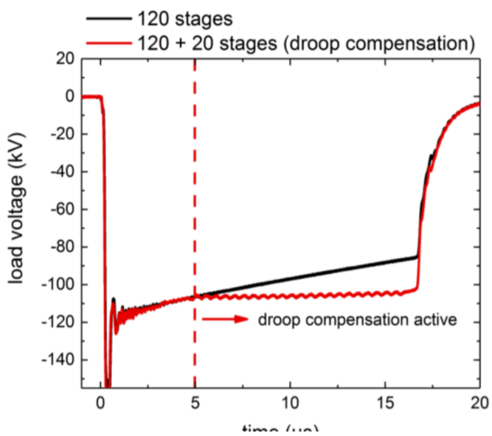


Fig. 2.2.3: Output voltage of the generator with droop compensation (red) in comparison to a pulse shape without droop compensation (black).

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 media (HTM) and storage media for CSP are a promising research area that will result in performance and efficiency increase and reduced costs. Within LIMCKA (Liquid Metal Competence Center KArlsruhe) several institutes and laboratories of the KIT 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 focus on compatibility research by surface optimization of existing materials using GESA and development of new materials that are able to form protective alumina scales. Besides liquid metal, efforts to explore the compatibility of the developed materials with other relevant advanced heat transfer media like solar salts were done in cooperation with colleagues from DLR.

Some of the tasks are embedded in European projects and cooperations like with DLR and EERA-CSP.

2.3.1 GESA – SOFIE

Separating the emitting plasma by a dedicated grid from the accelerating space allowed to control important parameters like emission current density and plasma production more independently. This results in several improvements of such new cathodes like improved angle distribution of the electrons, a better control of the emission area and stable emission currents above 0.4 A/cm2.

Laser-induced fluorescence-dip diagnostic to investigate in detail the electric field distribution was set-up and calibrated for stationary electric fields.

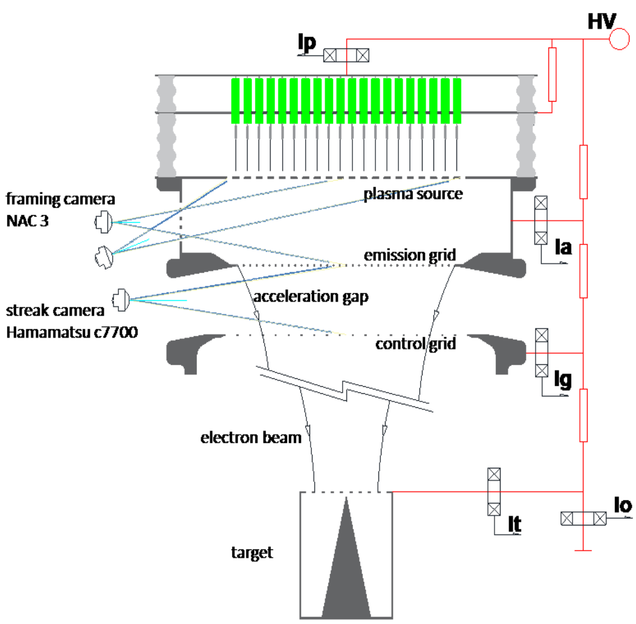


Fig. 2.3.1: Scheme of new cathode combined with high-speed diagnostic equipment

2.3.2 Material development

The focus on material development was on alumina-forming high entropy alloys (HEA) and alumina-forming austenitic (AFA) steels and FeCrAl for all liquid metals of interest (Sn, Na, Pb) and solar salts. Results for AFA materials in contact with liquid Pb are reported in respective chapter 3 (NUSAFE) in this report. HEA are a promising new class of materials for high temperature application in extreme environments like expected in liquid metal CSP systems. By adding Al an alumina-forming HEA can be manufactured. TEM investigations by colleagues from the IAM of specimens after 2000h exposure in Pb at 600°C showed the formation of an outer Al-oxide scale followed by an AlCr-oxide solid solution and an Al-oxide layer at the interface (Fig. X3). The total thickness of the entire protective layer after 200h at 600°C is around 100nm.

Selected FeCrAl alloys with 8wt% Al and 16wt% Cr and minor additions of Y and Zr were tested in a molten chloride salt after pre-oxidation in air. The alumina scale formed during the pre-oxidation was protective during the corrosion test performed at 800°C for 500h. It can prevent the common corrosion mechanism the diffusion of Cr into the liquid salt and the penetration of corrosive impurities into the alloy.

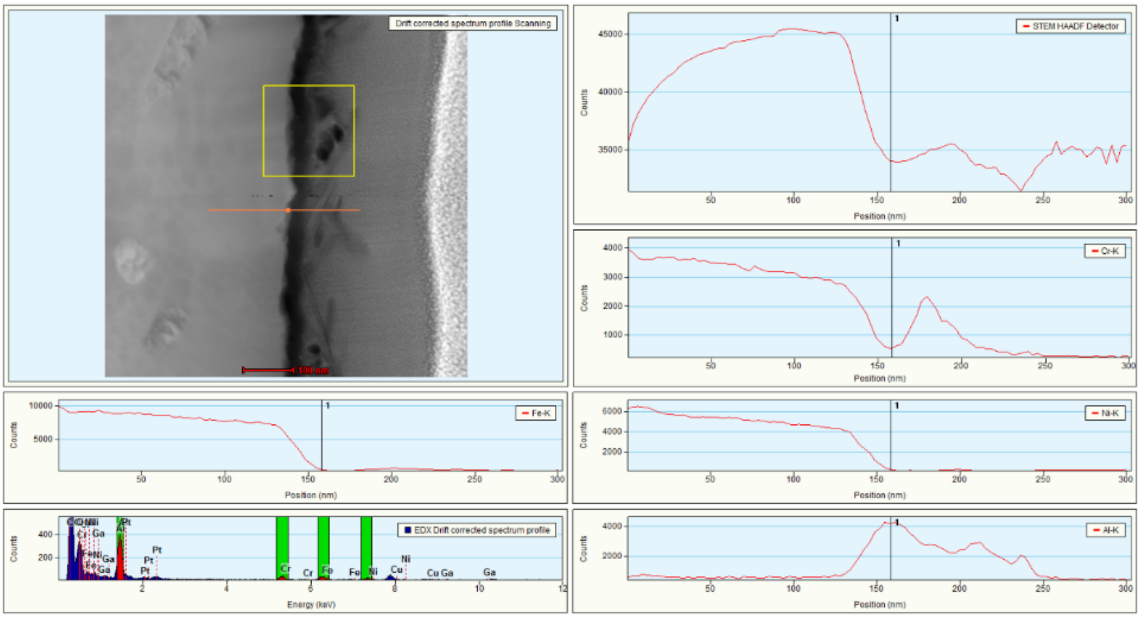


Fig. 2.3.2: TEM, EDX investigation of alumina forming HEA after 2000 exposure to Pb at 600°C

Involved Staff:

Frau Dr. S. Akaberi, W. An, Frau Dr. R. Fetzer, J. Fleig, **Dr. W. Frey**, Dr. Ch. Gusbeth, Frau Dr. A. Heinzel, D. Herzog, M. Hochberg, Dr. A. Jianu, F. Lindner, F. Lang, K. Leber, Prof. G. Müller, Frau N. Nazarova, A. Neukirch, **PD Dr. M. Sack**, D. Scherer, Dr. G. Schumacher (Guest), H. Shi (CSC-PhD student), Frau Dr. A. Silve, A. Sivkovich, R. Sträßner, **Dr. A. Weisenburger**, R. Wüstner, W. Zhen (CSC-PhD student)

Journal Publications

Polikovsky, M.; Fernand, F.; Sack, M.; Frey, W.; Müller, G.; Golberg, A. (2018). In silico food allergenic risk evaluation of proteins extracted from macroalgae Ulva sp. with pulsed electric fields. Food chemistry, 276, 735-744.

Robin, A.; Kazir, M.; Sack, M.; Israel, A.; Frey, W.; Müller, G.; Livney, Y. D.; Golberg, A. (2018). Functional Protein Concentrates Extracted from the Green Marine Macroalga Ulva sp., by High Voltage Pulsed Electric Fields and Mechanical Press. ACS sustainable chemistry & engineering, 6 (11), 13696–13705.

Silve, A.; Kian, C. B.; Papachristou, I.; Kubisch, C.; Nazarova, N.; Wüstner, R.; Leber, K.; Strässner, R.; Frey, W. (2018). Incubation time after pulsed electric field treatment of microalgae enhances the efficiency of extraction processes and enables the reduction of specific treatment energy. Bioresource technology, 269, 179–187.

Ding, W.; Shi, H.; Xiu, Y.; Bonk, A.; Weisenburger, A.; Jianu, A.; Bauer, T. (2018). Hot corrosion behavior of commercial alloys in thermal energy storage material of molten MgCl 2 /KCl/NaCl under inert atmosphere. Solar energy materials & solar cells, 184, 22–30.

Akaberi, S.; Wang, H.; Claudel, P.; Riemann, M.; Hause, B.; Hugueney, P.; Nick, P. (2018). Grapevine fatty acid hydroperoxide lyase generates actin-disrupting volatiles and promotes defence-related cell death. The journal of experimental botany, 69 (12), 2883–2896.

Buchmann, L.; Böcker, L.; Frey, W.; Haberkorn, I.; Nyffeler, M.; Mathys, A. (2018). Energy input assessment for nanosecond pulsed electric field processing and its application in a case study with Chlorella vulgaris. Innovative food science & emerging technologies, 47, 445–453.

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Robin, A.; Sack, M.; Israel, A.; Frey, W.; Müller, G.; Golberg, A. (2018). Deashing macroalgae biomass by pulsed electric field treatment. Bioresource technology, 255, 131–139.

Silve, A.; Papachristou, I.; Wüstner, R.; Sträßner, R.; Schirmer, M.; Leber, K.; Guo, B.; Interrante, L.; Posten, C.; Frey, W. (2018). Extraction of lipids from wet microalga Auxenochlorella protothecoides using pulsed electric field treatment and ethanol-hexane blends. Algal Research, 29, 212–222.

Voyer, D.; Silve, A.; Mir, L. M.; Scorretti, R.; Poignard, C. (2018). Dynamical modeling of tissue electroporation. Bioelectrochemistry, 119, 98–11

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

Contact: Prof. Georg Müller, Dr. A. Weisenburger

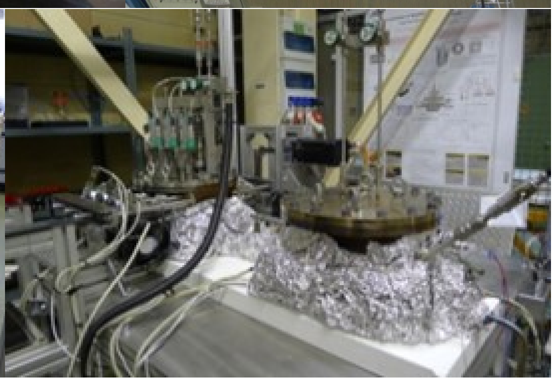
Long-living high-level radioactive waste from existing nuclear power reactors should be transmuted in short-living radio nuclides using fast neutrons provided by a spallation target in an accelerator driven subcritical system or by a fast nuclear reactor. The objective is to reduce the final disposal 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 to develop advanced corrosion mitigation processes based on in-situ formation of protective alumina scales 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 create aluminium containing surface alloys on steels. In addition, bulk alumina formers like FeCrAl, AFA (alumina forming austenitic steels) and HEA (high entropy alloys) are developed.

All tasks are embedded in European and international projects and cooperations like e.g., ILTROVATORE, MYRTE, GEMMA and EERA-JPNM.

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



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

Contact: Dr. Alfons Weisenburger

3.1.1 Optimizing the GESA IV facility

The GESA IV facility for the treatment of cladding tubes has a cathode and accelerator in cylindrical configuration, which still needs to be optimized to guarantee a reproducible and reliable surface alloying process. The optimized cathode design for higher current densities indicated a strong dependence of the voltage division between the cathode-grid gap and the grid-anode gap. Estimations show that an optimized design (ratio of grid and anode radius) can increase the target current by more than 30% (Fig. X1).

Electrons that miss the target and circulate in the accelerator volume negatively affect the operation performance of GESA IV. In order to reduce the number of circulating electron, the angular distribution of the electrons at emission needs to be minimized. This will be achieved by modification of plasma density, mesh size of grid and electric field strength in cathode-grid gap while fixing the emission current density.

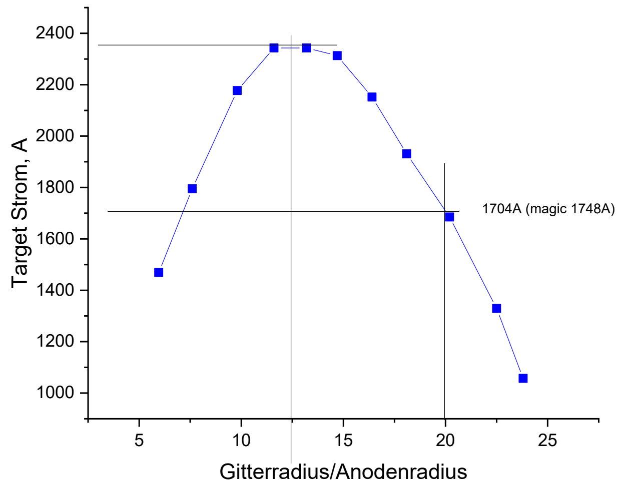


Fig. 3.1.1: Target current of GESA IV as function of the ratio of grid to anode radius.

3.1.2 Material development to mitigate corrosion

Fretting tests of wire wrapped fuel cladding samples were performed using the test facility FRETHME that was adapted to the MYHRRA relevant geometry in the framework of the H2020 project MYRTE. The tests were conducted at MYHRRA relevant conditions in PbBi at 400°C with a target oxygen content of 10^{-7} wt%. The amplitudes of the relative movement varied between 5 and 300 µm, the loads between 5 and 75 N and the duration between 100 h and 4080 h. The frequency was fixed to 10 Hz.

The penetration rates (µm/h) derived for the short term tests (100h to 500h) with varying loads and amplitudes are plotted versus the working rate (Fig. 3.1.2). At small amplitudes (<10µm) the fretting depths increases linearly with increasing load. At loads above 40N the fretting depths scales with increasing amplitude. Considering a 2 year operation time (17 520h) none of the penetration rates are acceptable considering an upper limit of 10% of the cladding wall thickness. It is known, that fretting damage is highest at the beginning and reduces by time. Results from the long term tests of 4080h depicted in the diagram on right side (blue dots) showed the lowest penetration rate of all experiments. The lowest rate measured at the long-term test sample 10N/60µm/4080h with 0.0031µm/h is low enough to satisfy almost the 10% target after 2 years for the penetration depth. In line contact, which would reduce the contact pressure significantly, the operating time until the 10% margin can be increased significantly.

Alumina forming austenitic alloys are developed as one of the advanced corrosion mitigation strategy with the support of the EU H2020 project GEMMA. An optimized alloy composition (*Fe-(2.5-4)Al-(14.5-16.5)Cr-(20-29)Ni + specific alloying element like Nb, W, Mo, C ….[wt.%])* was derived from corrosion tests in Pb at 550° and 600°C. Besides corrosion resistance, the AFA alloys should show ductile behaviour and are required to be stable regarding their microstructure during long term high temperature exposure. Small punch tests to examine the ductility of the alloys were performed by our colleagues at CIEMAT and proved that none of the tested AFA alloys showed brittle behaviour (Fig. 3.1.3)

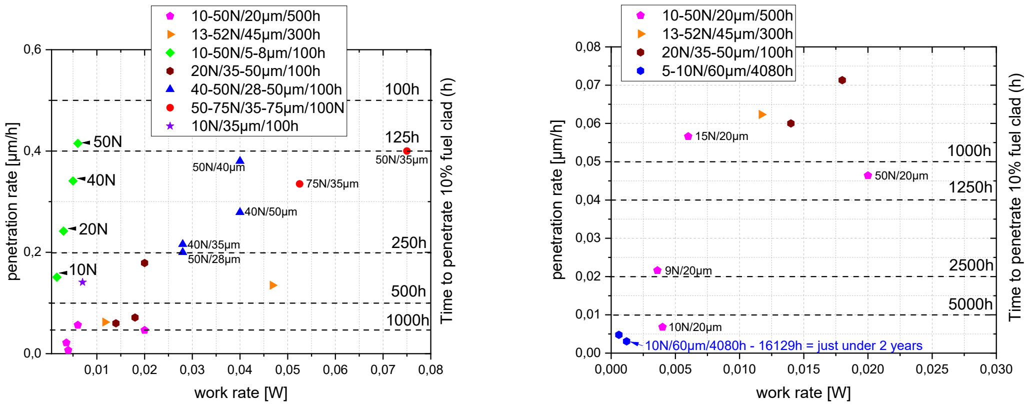


Fig. 3.1.2: Penetration rate vs working rate for different fretting conditions in molten PbBi with 10^{-7}wt% oxygen at 400°C; left side without long-term test / right side: with long-term test.

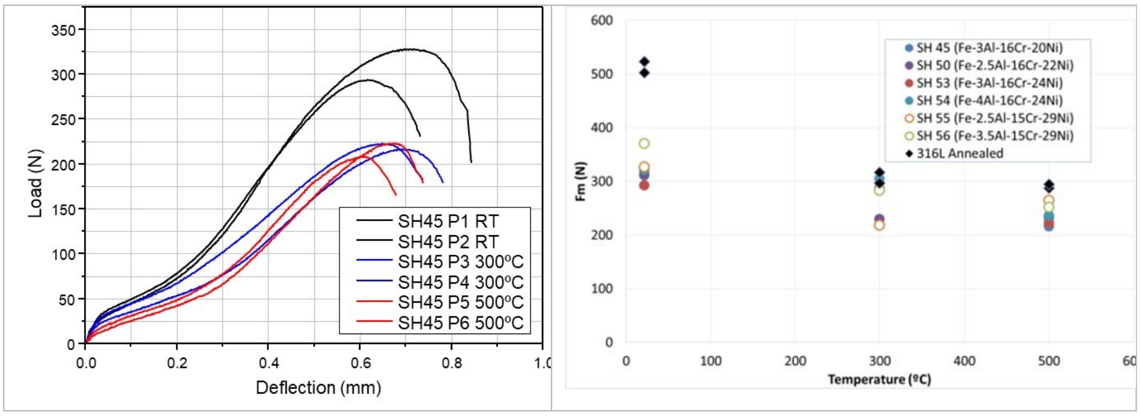


Fig. 3.1.3: Small punch test of AFA alloys showing the ductile behaviour of the new developed material.

XRD Measurement of AFA specimens exposed for 1000h in b at 600°C do not show any formation of ferritic phase due to the temperature and time. Small amount of γ' ($Ni_3(Al, Fe)$ that can act as aluminium reservoir are observed in some of the compositions.

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

Funding: EU-Projects and NUSAFE

Involved Staff

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

Journal Publications

Tang, C.; Jianu, A.; Steinbrueck, M.; Grosse, M.; Weisenburger, A.; Seifert, H. J. (2018). Influence of composition and heating schedules on compatibility of FeCrAl alloys with high-temperature steam. Journal of nuclear materials, 511, 496–507.

Hochberg, M.; Sack, M.; Herzog, D.; Weisenburger, A.; Müller, G. (2018). Design Validation of a Single Semiconductor-Based Marx-Generator Stage for Fast Step-Wise Arbitrary Output Waveforms. IEEE transactions on plasma science, PP (99), 1–7.

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-set 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 design of an industrial prototype reactor for the microwave assisted depolymerization of PET plastic waste, requested by the project partner Gr3n within the H2020 project SYMBIOBTIMA, for the purpose of energy efficient recycling, was successfully finished. This process idea gained the European Innovation Radar Prize 2018. In the frame of the H2020 Marie Curie international training network TOMOCON a microwave tomographic sensor is under development. 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. Two more projects have been started in 2018 for the microwave assisted and energy efficient lamination of synthetic leather for automotive industry (e-KOMFORT) and for the microwave assisted intermittent pultrusion of CFRP profiles (IMPULS) .

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 and novel process control concepts might be door openers for novel application that could not be satisfied with magnetron sources so far. Furthermore those novel microwave source 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. This new activity gained positive feedback from the 2018 mid-term review panel for the Helmholtz Energy Program.

4.1 Plasma Chemistry

Contact: Dr. Sergey Soldatov

The plasma assisted conversion of CO_2 into synthetic fuels based on renewable energies is considered as promising approach for mitigation of CO_2 emission and energy storage. Among different plasma discharges, namely the microwave sustained plasmas have shown to be most efficient for CO_2 splitting reaction $CO_2 \rightarrow CO + 1/2\ O_2$. The sustaining CO_2 plasma with short, nanosecond microwave pulses rather than with the continuous microwave power may increase the energy efficiency by shifting the thermal equilibrium in the plasma towards vibrational excitation states. Additionally, at pulse-mode operation the plasma gas temperature may be decreased considerably that opens the opportunity to combine the plasma activation with catalytic one as well as with gas separation membranes.

The plasma experiment is shown in Fig. 4.1.1. It comprises a plasma coaxial torch (Heuermann HF-Technik GmbH), a 300 W, 2.45 GHz solid state microwave generator (HBH Microwave GmbH), gas flow controllers, a X-STREAM Gas analyzer (Emerson) and an advanced optical emission spectroscopy (OES) system. The latter one features a high-resolution spectrograph (Acton SP-2756) with 750 mm focal length and 512x2048 pixel CCD camera (A-DH340-18U-03) with an intensifier and fast (≥2ns) gate from company LOT-QD GmbH.

In collaboration with IMVT the energy efficiency of CO_2 splitting in the plasma reactor was studied by systematic parameter variations, such as gas inflow (12, 15 and 18 slm), different duty cycles and pulse times with a 200 W pulse magnitude. Within that first parameter scan, a maximum energy efficiency of about 36 % war reached already for a duty cycle of 0.2 and an input gas flow of 12 slm. It corresponds to a specific energy input (SEI) of 0.05 eV/mol. Additionally the efficiency of the process in a pulsed microwave plasma has shown to be higher as compared with a plasma sustained with continuous microwave power.

Furthermore the combination of pulsed microwave plasma and catalysts was tested. The carrier material of the catalyst was a cordierite honeycomb monolith. First tests demonstrated a successful operation of the plasma reactor with the honeycomb monolith mounted in the plasma afterglow region without visible deterioration of the catalyst.

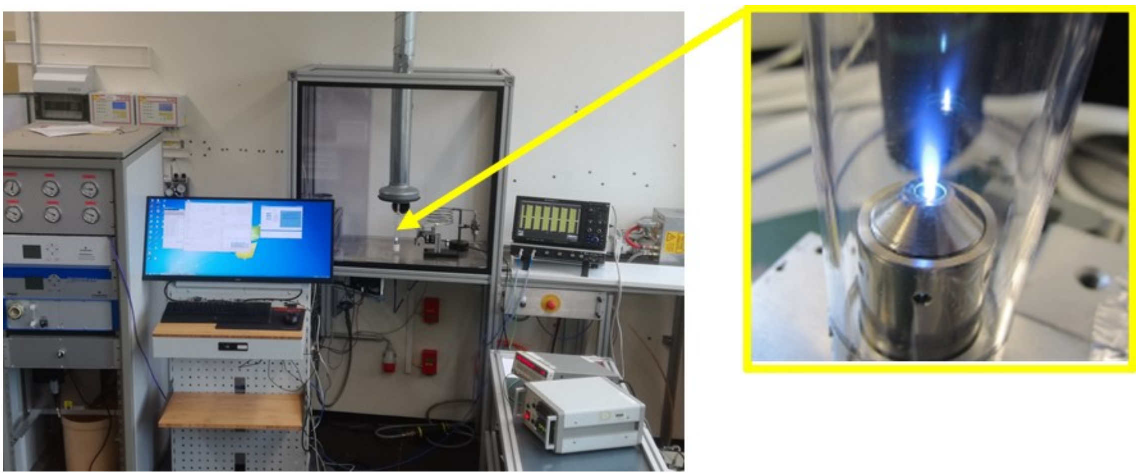


Fig. 4.1.1: Lab setup of the plasma experiment.

4.2 e-KOMFORT

Contact: M.Sc. Vasileios Ramopoulos

Comfort is increasingly a decision criterion for buying a car. High quality materials and comfort are the interface to the user. Today, cars are fitted with up to 9 m^2 of technical textiles, which make the car more attractive in terms of look and feel. Such decorative materials have to be laminated by very energy and time-intensive processes. With the conventional lamination technique the heat for adhesive activation is transferred by preheated tools via heat conduction through the surface of the decorative materials or substrate materials. Suitable microwave technology and suitable adhesives allow a direct and selective heating and activation of the adhesive. This leads to significant energy savings of more than 70% and to greater productivity. In Germany alone, the energy saving potential in this production area is estimated at approx. 70 GWh/year.

The project objectives are achieved by developing suitable formulations of a reactive hot melt adhesive and methods of applying this adhesive to the engineering fabric with sufficient uniformity and reproducibility. A suitable measurement setup is developed to enable the identification of the most suitable adhesive formulation (see Fig. 4.2.1). Then based on measured material properties microwave-compatible laminating tools are being developed for the microwave-assisted lamination of the textile thus pre-coated and prefixed to the substrate. Finally, a microwave technology is being developed, consisting of a microwave applicator with distributed, solid state microwave sources. By a targeted adjustment of those microwave sources in frequency, amplitude and phase the required field and temperature distribution shell be achieved in the adhesive layer. The optimized interaction of all of these developed technologies will demonstrate the process and its advantages on a pilot scale for selected automotive components at the end of the project.

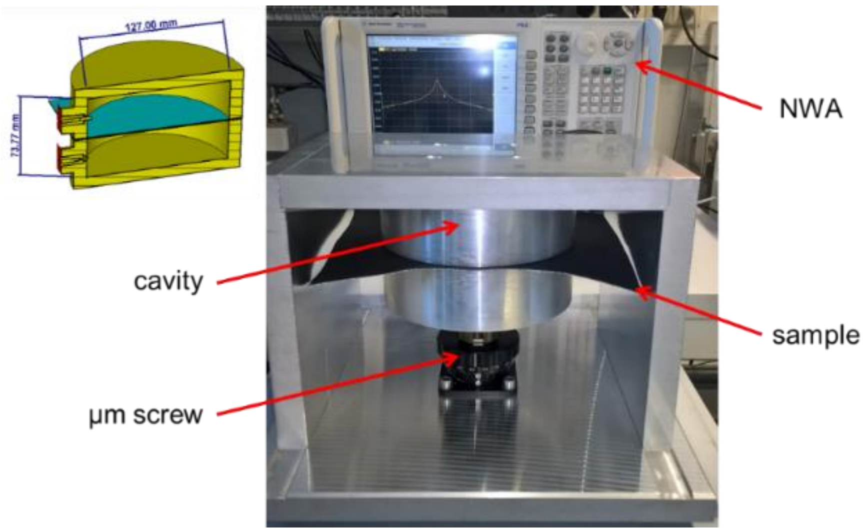


Fig. 4.2.1: Dielectric measurements setup for thin multilayer materials at 2.45 GHz.

Funding: 6th Energy Research Programme of the Federal Government, support code 03ET1576A

4.3 High power solid-state microwave generators

Contact: M.Sc. Dominik Neumaier

Microwave heating offers the possibility to reduce significantly the production cycle time and energy consumption in heating processes compared to conventional heating methods. The main challenge of microwave applicators in an industrial scale is the inhomogeneous dielectric heating of the products because of standing waves inside the microwave applicator. Therefore, the advantages of microwave heating cannot be used in every industrial application. The aim of this project is to develop a novel high power (1 kW, 2.4 GHz to 2.5 GHz) solid-state generator in cooperation with the company HBH Microwave GmbH (HBH) and use the advantages of this source in comparison with the commonly used magnetron oscillators to increase the temperature homogeneity of the heated product. In comparison to a magnetron a solid state amplifier increases the degrees of freedom of the microwave source because it’s possible to do a precise control in amplitude, phase and frequency in a very fast way (1 ms). Furthermore, this device also allows creating very fast pulses with a minimum pulse length of 10 ns.

The first 300 W prototype was produced by HBH and tested at KIT. A measurement setup was designed (see Fig. 4.3.1) and simulated for testing the advantages of the designed amplifier. By changing the frequency, it is possible to excite different eigenmodes with different heating patterns (see Fig. 4.3.1). The measured and simulated heating patterns are very similar. An optimized superposition of different eigenmodes increases the homogeneity of the heated workpiece. The next step is to do tests with different materials and use also the phase and amplitude control to further increase the homogeneity.

Another interesting application of this very fast controlled microwave source is the plasma application. By using of nanosecond microwave pulses it is possible to generate non-thermal plasmas at atmospheric pressures, which promises maximal conversion efficiency in plasma chemistry. Magnetron oscillators do not allow such fast pulses and therefore don’t provide this opportunity. A measurement setup was built and different tests are actually in progress (see Chapter 4.1).

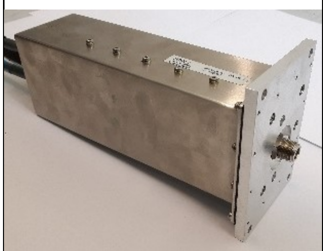
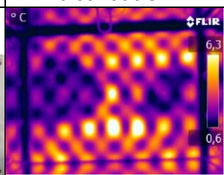
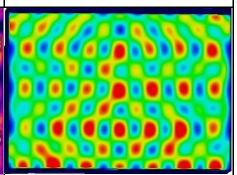
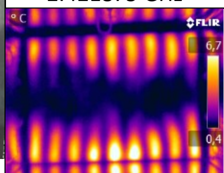
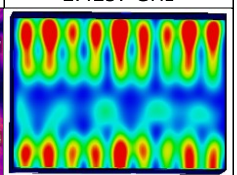
<table>
<tr><th>300 W Prototyp</th><th>Microwave oven</th><th>Measured temperature distribution</th><th>Simulated power distribution</th></tr>
<tr><td rowspan="2"></td><td rowspan="2"></td><td>
2.421875 GHz</td><td>
2.4257 GHz</td></tr>
<tr><td>
2.48322 GHz</td><td>
2.4922 GHz</td></tr>
</table>

Fig. 4.3.1: Prototype of a 300 W solid state microwave source, Microwave oven and comparison of measured and simulated modes

Funding: ZIM cooperation project, support code ZF4204602PR

4.4 REINFORCE

Contact: M.Sc. Julia Hofele

Carbon fibers are widely used in lightweight applications, but the carbon fiber production is rather expensive and energy intensive compared to the production of aluminium and steel. Microwave heating has the benefit of heating in the volume and thus may lead to faster heating rates. For this reason, the goal of the project is to research the production of carbon fibers with dielectric heating or microwave sustained plasma heating.

In a first step, fiber samples of conventionally stabilized PAN fibers and virgin PAN fibers provided by the project partner KCTECH were characterized dielectrically through the cavity perturbation method. For this purpose, a cylindrical cavity operating in the TM010 mode at a frequency of 2.45GHz was used. The results measured at room temperature show a difference in the dielectric properties at different reaction states. This leads to the assumption that the change in the dielectric properties allows in-situ characterization of the stabilization process and potentially enables innovative process control. The next step was to extend the measurement with controlled convective heating along any preset temperature profiles and measure the dielectric properties in-situ. The set-up schematics can be seen in Fig. 4.4.1.

In Fig. 4.4.2 a first result of the set up can be seen. It is obvious from the color change over the fiber length that the heating of the fiber is not yet homogenous due to heat losses so that the reaction also is not uniform over the fiber length. These first results show that the system parameters have to be adjusted. It is expected that the data acquired from the measurements will provide useful information about the reaction kinetics, which is important for the design of a microwave assisted stabilization process.

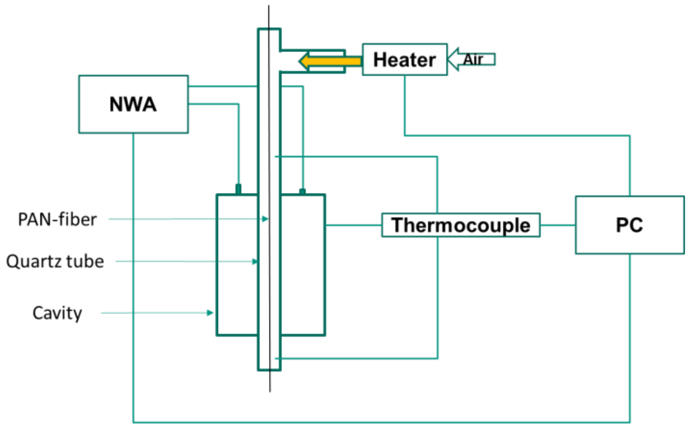


Fig. 4.4.1: Schematic of the set up for conventional heating and measurement of the dielectric properties.

Fig. 4.4.2: Conventionally heated fiber with inhomogenous reaction over the length.

Funding: ZIM cooperation project; support code ZF4204603SY7

4.5 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.

4 out of 15 doctoral researchers at 3 European academic institutes (Chalmers University of Technology, University of Eastern Finland and KIT), 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 the development and microwave and electrical capacitance tomography (MWT and ECT), respectively and its application in microwave drying of porous materials. Those are applied to detect the moisture distribution in a porous and to provide information to get a feedback for the process control. The technology finally is planned to be demonstrated on an industrial scale conveyor belt system for microwave assisted drying of polymer foams. In a first approach a virtual demonstration based on Simulink software has been developed, including process simulation, forward and inverse problem solvers for the ECT and MWT tomographic sensors as well as algorithms for process control.

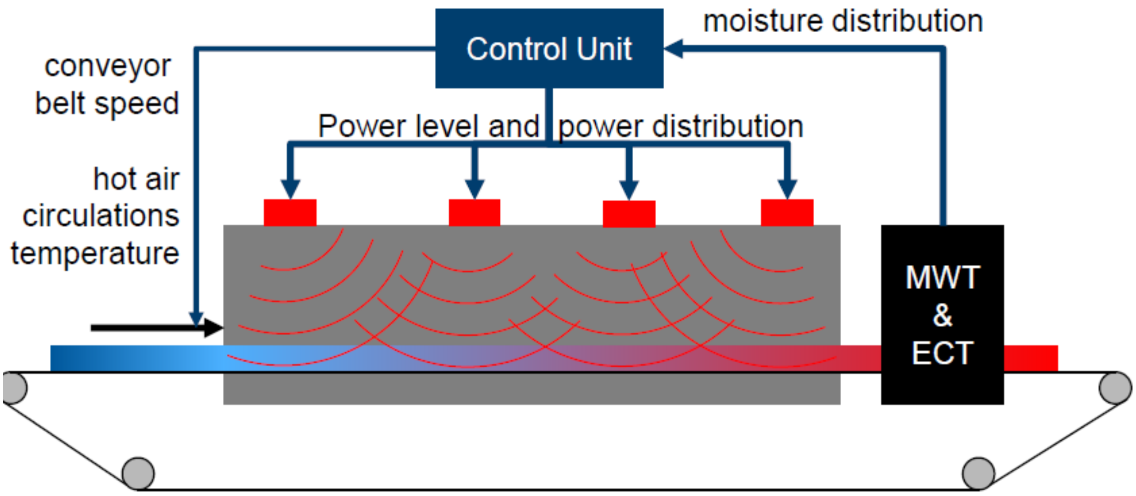


Fig. 4.5.1: Scheme of the microwave drying process and relevant process parameter to be controlled based on MWT or ECT data.

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

4.6 IMPULS

Contact: M.Sc. Moritz Engler

Pultrusion is a manufacturing process for the continuous production of fiber-reinforced polymer profiles, where reinforcing fibers are impregnated with a thermoset resin and then pulled though a heated die, which forces the material into the desired cross section and simultaneously cures the resin.

The IMPULS project aims to develop a microwave powered pultrusion system for the manufacturing of carbon fiber reinforced bicycle spokes. The advantage of microwave heating compared to the conventional heating process lies in the instantaneous volumetric heating of the structure. Since the tool surfaces are not heated, temporarily shutting down the microwave power allows the creation of uncured sections. Those uncured sections can then be rearranged in the desired shape cured in a secondary heating process. This expands the pultrusion process to a variety of new applications, which are not possible with conventional heating. A critical parameter for the usefulness of the uncured sections is the length of the undefined transitional areas between the fully cured and uncured profile sections. To achieve sharp transitions the heating zone of the microwave applicator needs to be as short as possible. For an applicator operating at 2.45 GHz this requires focusing of the electric fields to a fraction of the wavelength.

To design an applicator which achieves homogenous heating over the composite cross section, good knowledge of the electric properties of the composite is required. The material properties depend on the type of fiber and resin as well as the fiber volume content and therefore need to be determined for the specific application. Due to the conductive nature of the carbon fibers, unidirectional composites are highly anisotropic, behaving as a conductor if the electric field is aligned with the fibers and as a dielectric if it is perpendicular. For this reason a waveguide based transmission reflection method as shown in Fig. 4.6.1 is used for the characterization of the composite. It allows the measurement of highly lossy materials and also provides a defined orientation of the electric field, which is necessary for the independent measurement of the parallel and perpendicular polarization.

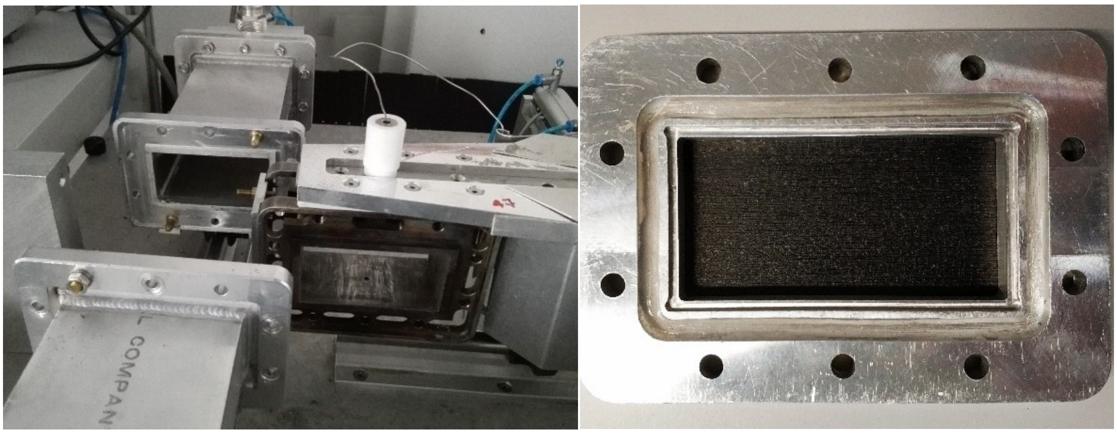


Fig. 4.6.1: Left: Transmission reflection test stand; Right: Composite sample in test frame

Funding: BMWi, ZIM Kooperationsprojekt, support code: ZF4204604BL8

4.7 3D Microwave Printing of Composites

Contact: Dr. Nanya Li

Continuous carbon fiber reinforced polymer composites are widely used in land transport and aerospace industry, because of their higher strength/weight ratio and longer service periods, compared with metal materials. Recently, the skyrocketing demands of 3D printing of continuous carbon fiber reinforced polymer composites stimulate the development of printing technologies. The popular printing technologies for composite materials include fused deposition modeling, digital light printing and laser-assisted laminated object manufacturing. Since every part can be sliced and printed in one direction, 3D printing technologies can build nearly any kind of parts. However, traditional 3D printing of continuous carbon fiber reinforced polymer composites lacks of abilities to manufacture parts with higher speed, cross-bars characters and higher strength. This is due to the slow heat transfer and weak bonding disadvantages during the traditional printing process. In this project, the 3D microwave printing technology is presented to fabricate continuous carbon fiber reinforced composites with higher speed and improved mechanical strength.

It is the first reported 3D microwave printer (3DMP) to manufacture parts by use of continuous carbon fiber reinforced polymer composites. An ingenious microwave printing head by taking the carbon fibers as a perfect microwave absorbing material was designed and manufactured. The printing path planning method was developed for the 3DMP of continuous carbon fiber reinforced composites. Under required load conditions, the stresses transmission path inside the composites were calculated and converted to the printing path of the continuous carbon fiber reinforced filament. A prototype system with 10 times faster printing speed than with conventional printing was demonstrated. This disruptive technology is clearly the answer to the next-generation lightweight carbon fiber reinforced composites manufacturing.

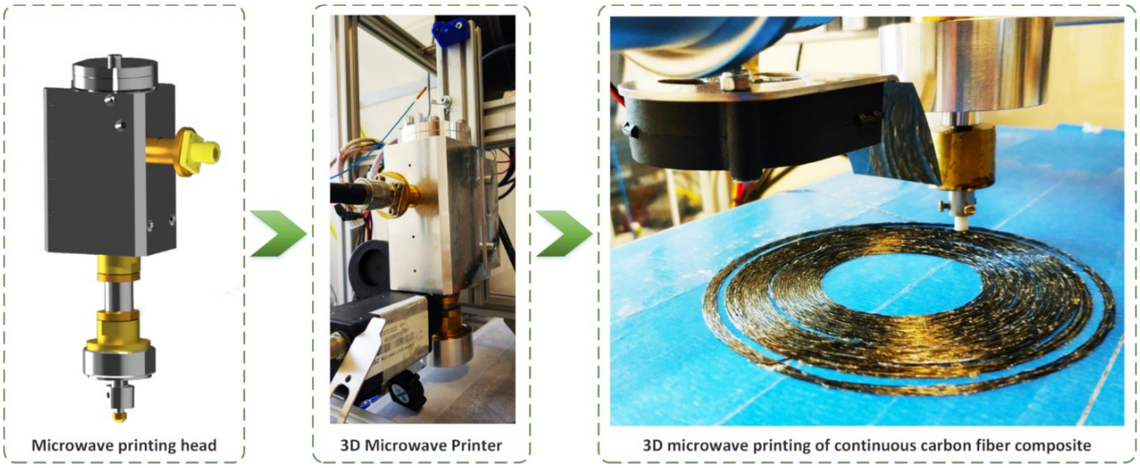


Fig. 4.7.1: 3D microwave printing technology of continuous carbon fiber reinforced composites.

Funding: Alexander von Humboldt Research Project, German Federal Ministry for Education and Research

Involved Staff

L. Baureis, Frau J. Frank, M. Engler, Frau J. Hofele, Prof. J. Jelonnek, S. Layer, Dr. N. Li, Dr. G. Link, D. Neumaier, V. Nuss, A. Omrani, V. Ramopoulos, T. Seitz, S. Soldatov, Frau S. Wadle

Journal Publications

Ramopoulos, V.; Link, G.; Soldatov, S.; Jelonnek, J. (2018). Industrial scale microwave applicator for high temperature alkaline hydrolysis of PET. International journal of microwave and wireless technologies, 10 (5-6), 709–719.

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 2018/2019 the total staff with regular positions amounted to 41 (20 academic staff members, 10 engineers and 11 technical staff member and others).

In addition 19 academic staff members, 1 engineer and 3 technical staff members (and others) were financed by acquired third party budget.

In course of 2018, 2 guest scientists, 12 PhD students (1 of KIT-Campus South, 11 of KIT-Campus North, 2 Scholarship, 1 in cooperation with IPP Greifswald), 1 DHBW student, 2 trainee in physics laboratory and 3 trainees in the mechanical and electronics workshops worked in the IHM. 5 Master students have been hosted at IHM and 4 Bachelor student has been at IHM during 2018.

Strategical Events, Scientific Honors and Awards

Prof. Manfred Thumm received the “IEEE 2018 NPSS Merit Award”.

Dr. Alfons Weisenburger was part of the Innovation Award of the gas industry.

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 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 2018, 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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