Pre-normative REsearch for Safe use of Liquid Hydrogen (PRESLHY)

Project Deliverable

Summary of experiment series E4.2 (Electrostatic) results

Deliverable Number:	4.5 (D28)
Work Package	4 (Ignition)
Version	1.1
Author(s):	A. Friedrich PS, A. Veser PS T. Jordan, KIT
Submitted Date:	28 August 2020
Due Date:	31 May 2020
Report Classification:	Confidential

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 779613.

History		
Nr.	Date	Changes/Author
1.0	26.6.2020	DOI https://doi.org/10.5445/IR/1000096833 as KITopen references
1.1	16.3.2021	Integrated Cryostat discharges

Key words

Cryogenic release, high pressure, electrostatic field

Preface and Disclaimer

After initial discussions the test program for cryogenic hydrogen releases was split into high pressure releases at temperatures down to 80K (part A) and a low pressure liquid hydrogen temperature part (part B). However, because of certain adaptions the electrostatic build-up/ignition experiments planned for the last project phase could be addressed in combination with these experiments, i.e. considerably earlier.

This report contains the "meta data" of the respective experiments, providing detailed description of the experimental set-ups, sensors, result data structure and access (sub-set of the result data is provided via KITopen). Detailed evaluation of the results, e.g. determining the discharge coefficient, as well as any modelling work is excluded here and left for subsequent work.

Because of the interrelation with the published result data it is intended to turn this confidential report into a public one.

Despite the care that was taken while preparing this document the following disclaimer applies: The information in this document is provided as is and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof employs the information at his/her sole risk and liability.

The document reflects only the authors' views. The FCH JU and the European Union are not liable for any use that may be made of the information contained therein.

Acknowledgements

The PRESLHY project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 779613.

Publishable Short Summary

In the frame of the PRESLHY project more than 200 hydrogen blow-down experiments were made with the DisCha-facility at KIT and about half of the experiments were made at cryogenic temperatures (approx. 80 K). During the experimental campaign the facility was continuously improved and extended, since several problems with the facility and the instrumentation were encountered. However, the tests showed very good reproducibility. Besides the discharge characteristics and the transient jet behavior also the electrostatic fields have been recorded to understand potential mechanisms for spontaneous ignition.

Another 12 experiments were performed with the Cryostat-facility of which 7 experiments were done with liquid hydrogen. Due to restrictions of the cryostat vessel only pressures up to 5 bar could be investigated in these experiments. Despite the low initial pressures considerable electric fields were measured.

Although especially the cold jets at approx. 80 K and 30 K generated relative strong electrostatic fields, not a single test showed a spontaneous ignition. The observed static electricity seems to be generated by ice crystal which form on the release nozzle before the tests.

Table of Contents

Key words ii
Preface and Disclaimer ii
Acknowledgements ii
Publishable Short Summary iii
1 Purpose of the Tests – Knowledge Gap Addressed 1
2 General Description of the Experimental Set-up 2
2.1 DisCha facility 2
2.2 Cryostat facility 4
3 Instrumentation of the facilities 4
3.1 DisCha facility 4
3.2 Cryostat-facility 5
3.3 Estimate of Measurement Errors 7
4 Test Matrix 8
4.1 DisCha facility 8
4.2 Cryostat facility 10
5 Structure of Experimental Result Data 11
5.1 DisCha Datasets explained with Cold Case 20190503_112024 11
5.2 Cryostat Datasets explained with Cold Case 20200521_113404 13
6 Short Summary of Results 14
6.1 DisCha-Experiments with Field Mills 14
6.2 Cryostat-Experiments 18
7 Summary, Conclusions and Outlook 20
8 References 21

1 Purpose of the Tests – Knowledge Gap Addressed

In the work package WP4 of the PRESLHY project the electrostatic fields potentially generated by the transient multiphase releases in a high-pressure cryogenic discharge have been investigated by the project partners Karlsruhe Institute of Technology (KIT) and Pro-Science (PS).

Due to technical reasons two facilities had to be used in the experiments:

1. The DisCha facility is utilized to generate discharges and transient jets of hydrogen at ambient and cryogenic temperatures (approx. 80 K, temperature of boiling nitrogen (LN2)) and pressures up to 200 bar. The facility was integrated in a larger experimental set-up. The set-up was installed on the free field behind the main hall of the hydrogen test site HyKa at KIT (see Figure 1**Fehler! Verweisquelle konnte nicht gefunden werden.**, left).
2. The Cryostat facility is used for releases of liquid hydrogen (approx. 30 K, LH2) from pressures up to 5 bar. Due to safety reasons and since the experiments were part of a series of experiments with LH2 the facility was built close to the LH2 supply trailer on a free-field-test site in the woods a few kilometers to the north of KIT Campus North (see Figure 1, right).

Figure 1: Location of DisCha-facility in a tent behind the main hall of the hydrogen test site HYKA at KIT and setup for the Cryostat-experiments with LH2 on the free-field test site north of KIT-Campus North.

The main purpose of the tests was to provide validation or reference data for

- models defining or using a discharge coefficient (see experiments E3.1a),
- subsequent explosion tests, where the released gases will be ignited (see experiments E5.2), and
- electrostatic field excitation and associated ignition potential of high-pressure hydrogen gas jets.

at cryogenic temperatures. This report focusses on the electrostatic effects and the associated potential for ignition, which are the scope of the experimental series E4.2.

2 General Description of the Experimental Set-up

2.1 DisCha facility

The DisCha facility mainly consists of a stainless-steel pressure vessel with an internal free volume of 2.815 dm³ and a weight of about 28 kg, which is fastened in an insulated box for the LN2 pool cooling (Remark: the original plan to cool the DisCha facility with a LH2 pool was discarded because of the high costs and the volatile boiling behavior expected for LH2, and because the pressure vessel was only designed for LN2 boiling temperature).

The cooling box with the vessel is mounted on a sledge and this sledge is mounted on a balance. The total weight of the experimental set-up, as measured by the balance is about 120 kg. Photographs of the facility and a sketch of the facility are shown in Figure 2 and Figure 3.

Figure 2: Photographs of the pressure vessel (left) and the general set-up of the DisCha-facility (right)

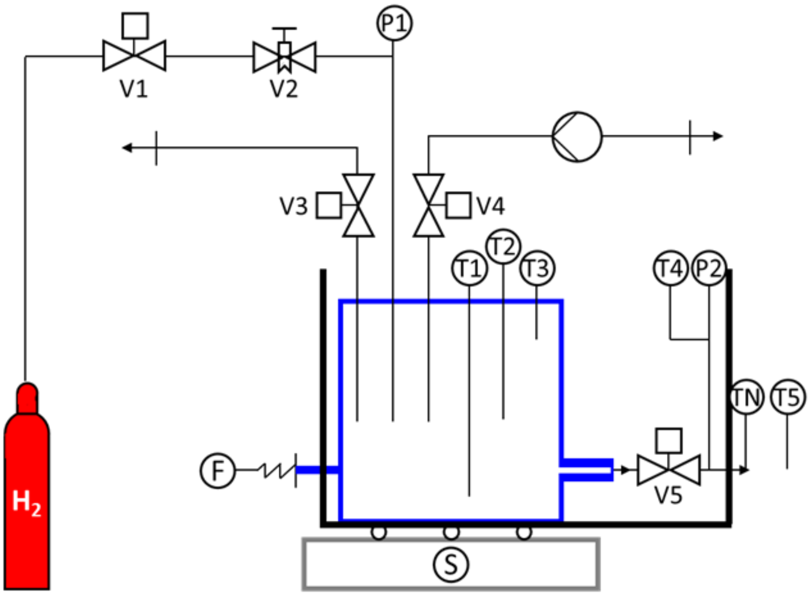


Figure 3: Sketch of the DisCha-facility
(DisCha in blue color, cooling box in bold black color, balance in grey color)

Through the filling line and the valves V1 and V2 the test vessel can be filled with hydrogen up to pressures of 200 bar from a bundle of hydrogen bottles. The vessel is equipped with several ports for instrumentation on its top and a rod that points on a force sensor on its rear side. Opposite to the force sensor a tubular exhaust pipe is welded to the vessel, where release nozzles with different aperture sizes, nozzle diameters respectively, can be fastened.

The sledge provides an almost slip free movement of the setup for the measurement of the repulsive forces, that act on the vessel during the release experiments. The balance is used to measure the loss of weight caused by the effusing gas in the hydrogen release experiments.

Four nozzles with circular apertures of 0.5, 1, 2 and 4 mm were used in the experiments. The nozzles were mounted from outside the pool to the tube that connects them to the release valve (Figure 4). Another connection, which is kept as short as possible, is mounted in between the release valve and the vessel exhaust

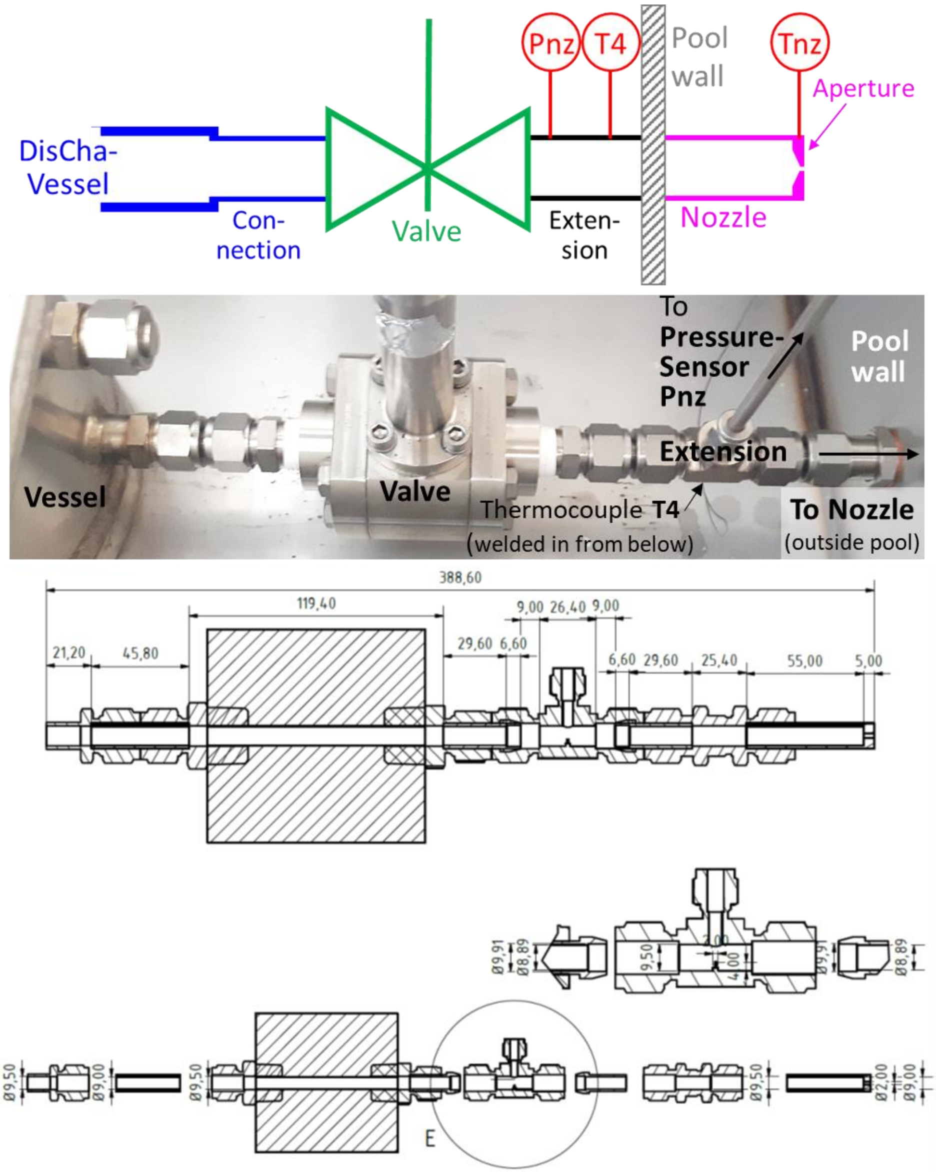


Figure 4: Sketch and photo of the release pipework of the DisCha-facility and technical drawing of the complete release branch with the 2 mm nozzle (only the diameter Ø 2 is changed for the other nozzles). Shaded rectangle corresponds to release valve, where no measurements are possible.

2.2 Cryostat facility

In contrast to the DisCha-facility the Cryostat-facility allows storing LH2, but as for most cryo-vessels, its storage capacity is limited to an internal pressure of 6 bar. The vessel has a volume of 225 dm³, which is protected against heat ingress from the outside by a shield of LH2 in between to vacuum layers (see Figure 5).

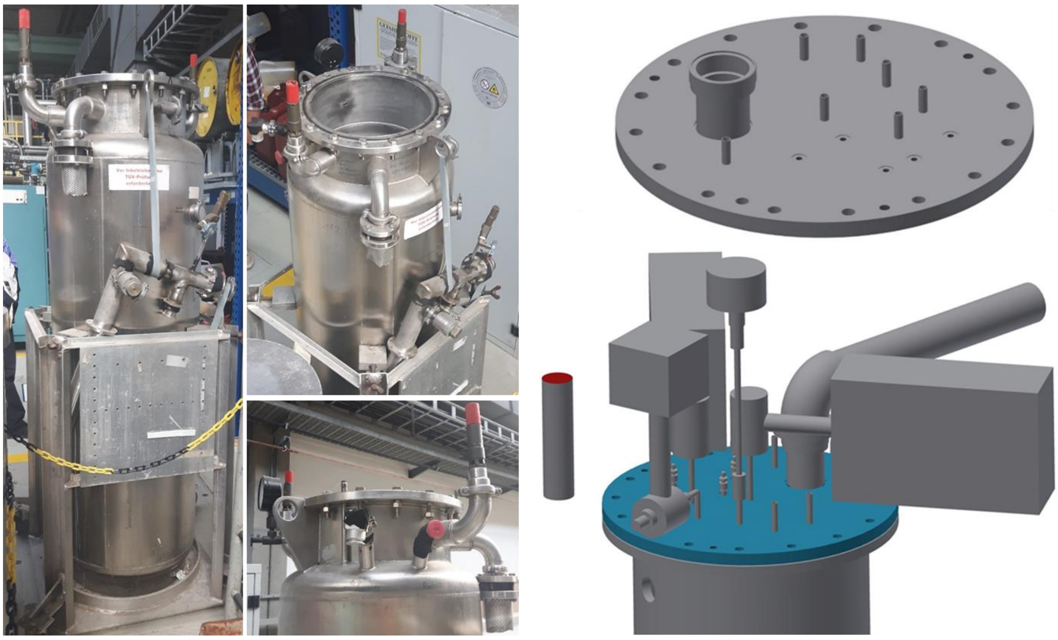


Figure 5: Photos of the Cryostat-facility and technical drawing of the lid fabricated to house the components needed to realize a connection to the LH2-trailer as well as for a LH2-release through the same release branch as it was used in the DisCha-facility.

For the experiments with the Cryostat facility a special lid was fabricated that houses all components needed to realize a connection to the LH2-trailer as well as for a LH2-release through the same release branch as it was used in the DisCha-facility (see Figure 4 and Figure 5, right).

The vessel is filled using the super insulated vacuum hose provided by Air-Liquide together with the LH2-Trailer. For the control of the filling level a set of 5 thermocouples in different heights inside the vessel as well as a balance that measures the mass of the complete assembly are used.

3 Instrumentation of the facilities

3.1 DisCha facility

Field-measurements are main focus of this report on electrostatics. This is why in this and all following chapters only DisCha-experiments performed after the end of April 2019 are described in which field mills for electrostatic measurements were used. For the same reason only the part of the instrumentation that is necessary for the field measurements will be described here, all further information on sensors used and other experiments shall be referred to the report on the unignited DisCha-experiments of WP3.1 (D3.3a, Experimental Investigation of Cryogenic Hydrogen Release and Dispersion). Apart from the force sensor and the balance (F and S in Figure 3) mentioned above, the test vessel and the release nozzle are instrumented with two pressure sensors and eight thermocouples. Outside the release nozzle further five thermocouples and a set of five H2-concentration measurement devices are installed. Additionally, two field mills for measuring static electric field strength and three cameras (2 photo cameras and 1 video camera) are used to monitor the releases using the BOS-technique for the visualization of density gradients.

Pressure sensors: One static pressure sensor (P1 in Figure 3) in the filling line is used to control the initial pressure inside the vessel during the filling procedure, while the second one measures the pressure changes in the release line. Since the second sensor is connected to the tube in between release valve and nozzle, the first increase in this signal corresponds to the actual start of the release. After the initial pressure built-up in the release line both pressure sensors capture the pressure decrease inside the vessel during the experiment.

Field mills: The measurement of the electrostatic fields was realized with field mills (model Kleinwächter EFM 113B) that were positioned in the height of the nozzle in distances of 0.5 and 1.5 m from it and with horizontal distances of 0.9 m from the jet axis (Figure 6).

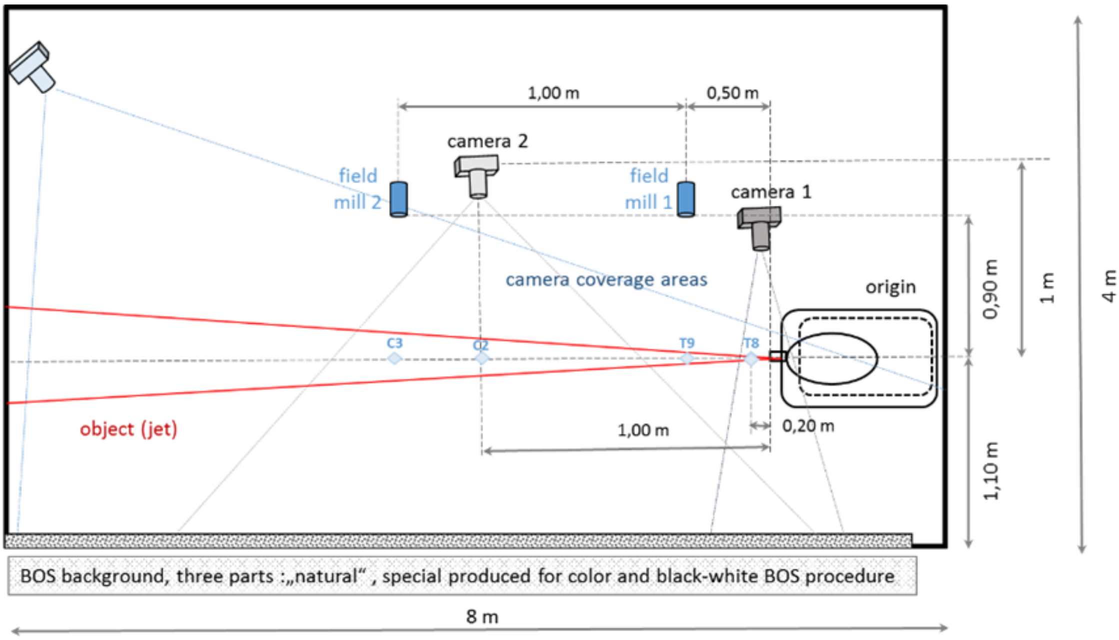


Figure 6: Sketch of the positions of the field mills and the cameras in the DisCha-facility (top view)

3.2 Cryostat-facility

The complete Cryostat-facility was mounted on a scale (Figure 7, Mettler-Toledo, Type: PFK989, Range: 0 - 600 kg) to monitor the filling level of the vessel during the filling procedure and the release experiment. Special care was taken to eliminate influences of wires and hoses. The filling level of the vessel was also monitored using 5 thermocouples that were installed inside the vessel in different heights. Similar to the DisCha-facility one pressure sensor was used to record the pressure inside the vessel throughout the complete experiment. Since the same release branch as in the DisCha-experiments is used, a second pressure sensor and a thermocouple are installed to the junction in the release line between release valve and nozzle. Both pressure sensors are the same as in the DisCha experiments

(WIKA, Type: S-20, Range: 0 - 250 bar(rel.)), and also the thermocouple was unchanged since it cannot be removed from this junction.

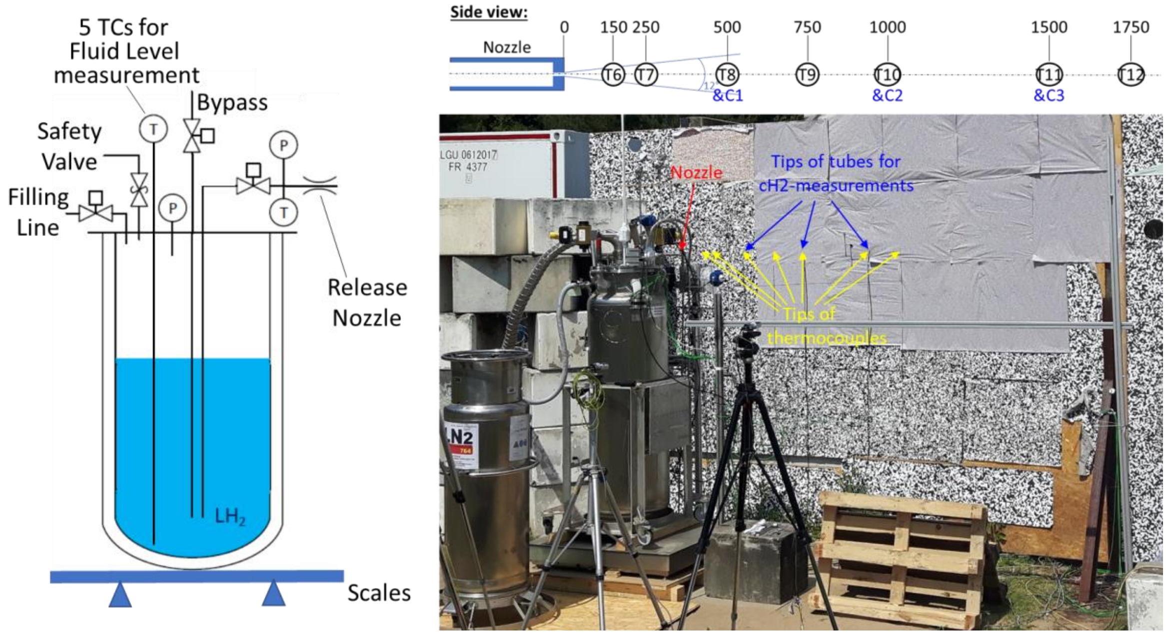


Figure 7: Sketch and Photo of the Cryostat-facility with details of the instrumentation.

Outside the release nozzle further seven thermocouples and a set of three tubes for sample taking for H2-concentration measurements are installed in positions on the centerline of the jet. For the concentration measurements tubes had to be used to provide a constant gas flow from the sampling position to the sensor.

Three field mills for measuring static electric field strength and five cameras (2 photo cameras (C1 and C2), 2 video cameras (P1 and P2) and 1 Thermocamera (IR)) are distributed besides the cold jet to monitor the releases using the BOS-technique for the visualization of density gradients (see Figure 8).

In the Cryostat-experiments the same pressure sensors and field mills were used as in the DisCha-experiments.

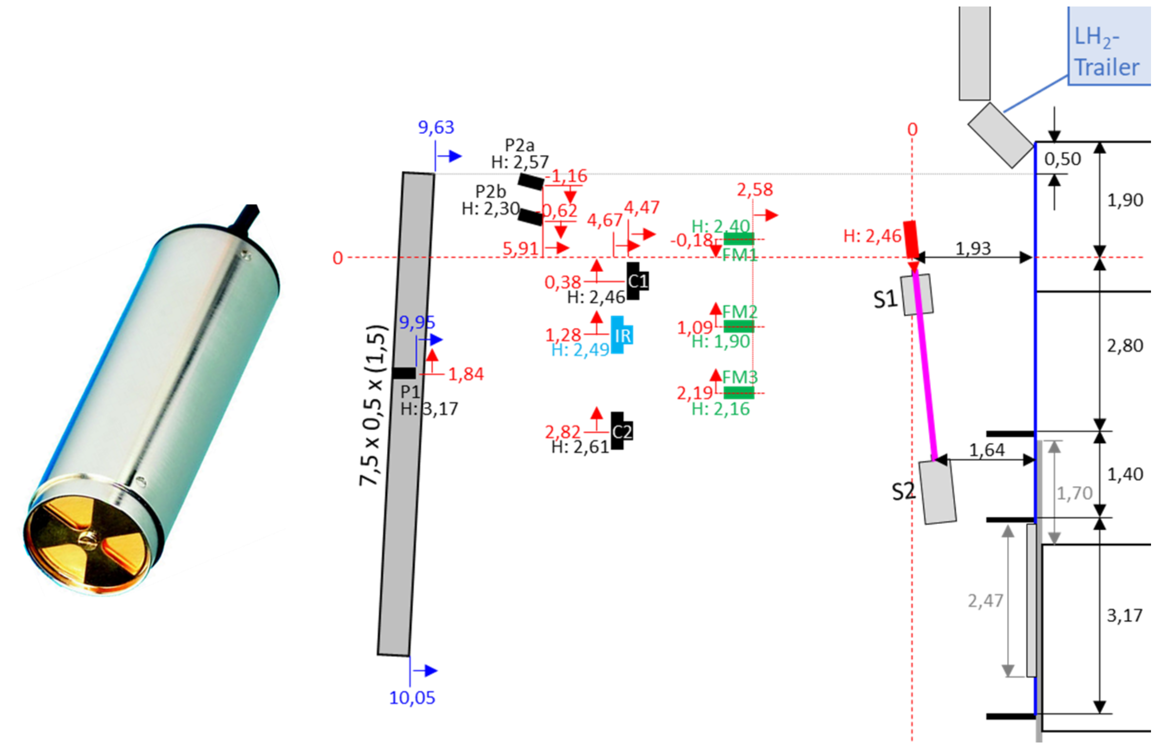


Figure 8: Field mill of type Kleinwächter EFM 113B (left) and sketch of the Cryostat-facility with details of the instrumentation (right).

3.3 Estimate of Measurement Errors

The accuracy of the sensors used in the experiments is given in Table 1. The values were taken from the respective manuals for ambient temperature conditions. For cryogenic temperatures no data is available. In the experiments neither pressure sensors nor field mills were in direct contact to the cold hydrogen, so the accuracy for ambient temperature seems to be sufficient. All sensors were used in both series.

Table 1: Accuracy of the pressure sensors and field mills used in the DisCha- and the Cryostat-experiments

Sensor	Manufacturer	Type (Range)	Non-linearity @ 290 K
Pressure	WIKA	S-20 (250 bar)	< 0,125% FS
Field mill	Kleinwächter	EFM 1138 (5 kV/m)	< 5% FS

4 Test Matrix

4.1 DisCha facility

With the DisCha-facility in total 214 experiments were performed for WP3.1a, and in 123 of these experiments field mills were used. The field mills were added to the set-up in its final stage (end of April 2019), with which the complete matrix was repeated at least once. The test matrix for the blow-down experiments was constructed by varying the release nozzle diameter (4 diameters: 0.5, 1, 2 and 4 mm) and the initial hydrogen storage pressure (7 nominal pressure values: 5, 10, 20, 50, 100, 150 and 200 bar) for two hydrogen storage temperature levels (2 nominal storage temperatures: 80 and 300 K). For the cold experiments several repetitions were made, while only few warm experiments were repeated to provide an estimate for the stability, reproducibility respectively, of the measurement system in general.

The whole DisCha test campaign lasted almost 4 months (middle of February to end of June 2019) with several interruptions for improving the measurement set-up, setting up the pre-cooling or because of delays in LN2 supply. Into this report only experiments with field mills are included, which were all performed after end of April 2019. In the following two tables for the test matrix at ambient and cryogenic temperature a test is labeled with the date and time ("date"_"time"), at which the test was initiated:

2019**MMDD_hhmmss**

with **MM** for month, **DD** for day, **hh** for hour, **mm** for minute, **ss** for second of the formal start of the experiment (see Table 2 and Table 3).

Table 2: Test matrix of the DisCha experiments with field mills at ambient temperature

		Nozzle-Diameter [mm]			
		0.5	1	2	4
Pressure [bar]	5	20190523_155208	20190523_151618	20190523_144219	20190523_141327
	10	20190523_154849	20190523_151411	20190523_144022	20190523_141008
	20	20190523_154414	20190523_151013	20190523_143801	20190523_140705
	50	20190523_153958	20190523_150640	20190523_143501	20190523_140344 20190624_145615
	100	20190523_153415	20190523_150133	20190523_143020 20190624_152500	20190523_115747 20190624_145052
	150	20190523_152829	20190523_145700	20190523_142651 20190624_151944	20190523_113338 20190624_144205
	200	20190523_152309	20190523_144939	20190523_142245 20190624_151045	20190523_113015 20190624_143040
Excel-file		Sheet(s)	Sheet(s)	Sheet(s)	Sheet(s)
PRE4P2_KIT_DisCha_Dall_290K		**20190523-290K-05mm**	**20190523-290K-1mm**	**20190523-290K-2mm** **20190524-290K-2mm**	**20190523-290K-4mm** **20190524-290K-2mm**

Table 3: Test matrix of the DisCha experiments with field mills at LN2-temperature

		Nozzle-Diameter [mm]			
		0.5	1	2	4
Pressure [bar]	5	20190509_143959 20190509_144955 20190604_151150 20190604_153521	20190507_155308 20190507_160047 20190531_120333	20190430_150817 20190430_151117 20190531_103828	20190503_112024 20190503_112408 20190528_111918
	10	20190509_142254 20190509_143252 20190604_150515 20190604_152905	20190507_153753 20190507_154609 20190531_115603	20190430_144909 20190430_150600 20190531_103408	20190503_110955 20190503_111525 20190528_111240
	20	20190509_111108 20190509_112201 20190604_145638 20190604_152254	20190507_152321 20190507_153041 20190531_114903	20190430_143105 20190430_144308 20190531_102810	20190503_110259 20190503_121635 20190528_110441
	50	20190509_135757 20190509_141151 20190604_144425	20190507_150252 20190507_151256 20190531_113940	20190430_141445 20190430_142546 20190531_101948	20190503_115334 20190503_120719 20190528_105437
	100	20190509_132731 20190509_134535 20190604_142752	20190507_143257 20190507_144631 20190531_112944	20190423_120305 20190430_111836 20190430_114028 20190531_101249	20190503_104121 20190503_105250 20190528_112837 20190528_143608
	150	20190509_104138 20190509_105744 20190604_140657	20190507_135605 20190507_141457 20190531_111808	20190423_121441 20190430_135153 20190430_140732 20190531_100257	20190503_100144 20190503_102600 20190528_142048
	200	20190509_100955 20190509_102557 20190604_134543	20190531_110440	20190430_102456 20190430_110643 20190531_094951	20190503_134536 20190503_140045 20190528_104204
Excel-file		Sheet(s)	Sheet(s)	Sheet(s)	Sheet(s)
PRE4P2_KIT_DisCha_Dall_80K		**20190509-80K-05mm 1** **20190509-80K-05mm 2** **20190604-80K-05mm 3** **20190604-80K-05mm 4**	**20190507-80K-1mm 1** **20190507-80K-1mm 2** **20190531-80K-1mm 3**	**20190430-80K-2mm 1** **20190430-80K-2mm 2** **20190431-80K-2mm 3** **20190423-80K-2mm 4**	**20190503-80K-4mm 1** **20190503-80K-4mm 2** **20190528-80K-4mm 3** **20190528-80K-4mm 4**

To reduce the amount of data to be published with this report only channels with direct relation to the scope of this work-package are selected for publication. These channels comprise the signals of the two field mills and the pressure measurements inside the vessel and inside the nozzle. The signal courses of one experimental series with one nozzle at one day are stored, together with the data of the initial and ambient conditions, in one Excel sheet. In case of several series with the same nozzle at the same temperature several Excel sheets are created. The sheets are grouped in two Excel-files for measurements at the same initial temperature (approx. 80 K and 290 K). The data structure is also visualized by differently colored fonts in the above tables for the test matrix.

4.2 Cryostat facility

With the Cryostat-facility 12 release experiments were performed for WP3.1b, and in all experiments three field mills were used. In 7 of the tests liquid hydrogen (LH2) was released from the Cryostat, while in 5 reference tests gaseous hydrogen at ambient temperature was used. The Cryostat test campaign was done in May 2020 directly after the COVID19-shutdown in Germany. The first day the reference experiments at ambient temperature were made, while the cryogenic tests were performed the following day (21st of May 2020). In the following test matrix for ambient and cryogenic temperature a test is labeled with the date and time (“date”_”time”), at which the test was initiated:

2020**MMDD_hhmmss**

with **MM** for month, **DD** for day, **hh** for hour, **mm** for minute, **ss** for second of the formal start of the experiment. The test matrix for the blow-down experiments was constructed by varying the release nozzle diameter (2 diameters: 2 and 4 mm) and the initial hydrogen storage pressure for two hydrogen storage temperature levels (2 nominal storage temperatures: 30 and 300 K). Due to the limited maximum pressure of the Cryostat vessel only a limited number of initial pressure levels was possible (pressure values in between 2 and 5 bar). The test matrix for the Cryostat-experiments is shown in Table 4.

Table 4: Test matrix of the Cryostat experiments

		Initial Storage Temperature [K] 290 K		30 K	
		Nozzle-Diameter [mm] 2	4	Nozzle-Diameter [mm] 2	4
Pressure [bar]	3,2	20200520_144544	20200520_150010		
	4,75		20200520_150332		
	5	20200520_143103	20200520_145506		
	2				20200521_114818
	3,25			20200521_133851	20200521_111302
	4				20200521_101847 20200521_121012
	4,25			20200521_125654	
	4,5				20200521_113404

Excel-file	Sheet	Sheet
PRE4P2_KIT_Cryostat_Dall_290K	**20200520-290K 2mm** **20200520-230K 4mm**	
PRE4P2_KIT_Cryostat_Dall_30K		**20200521-30K 2mm** **20200521-30K 4mm**

The data extracted from the original data files was prepared for publication similarly to the DisCha-data and so two Excel files with the pressure and field mill records for the two initial storage temperatures were generated. Due to the limited number of experiments all data of all series with one nozzle could be collected in one sheet.

All datasets referred to here in this report are published via https://doi.org/10.5445/IR/1000096833 on KITopen [1].

5 Structure of Experimental Result Data

5.1 DisCha Datasets explained with Cold Case 20190503_112024

The result data, the datasets respectively, are stored in two Microsoft Excel files (extension *.xlsx) with the facility name (in this case "DisCha") and the hydrogen storage temperature (either 80 K or 290 K) in the name. Each Excel file consists of several worksheets and each worksheet corresponds to one experiment series performed at one day with one nozzle diameter at one temperature. So the worksheets are named with the format "2019MMDD_Dmm_ttK_x" with "mm" indicating the nozzle diameter ("05","1","2" or "4") and "tt" indicating the nominal start temperature ("80" for LN2 boiling or "290" for ambient). If several such series exist for one nozzle diameter further Excel-sheets are generated and distinguished with increasing end number ("x" at end of sheet name). In the above Table 2 and Table 3 the arrangement of the datasets in different series is visualized by different colors in the respective columns.

So, for example the cold case experiment with the 4 mm nozzle that was conducted the 03rd of May 2019 at 11:20 am at an initial pressure level of 5 bar bears the name "20190503_112024" and can be found right at the top of the right column in Table 3. According to the font color and the bottom lines of the table the data of this experiment can be found in the sheet "20190503-80K-4mm 1" of Excel file "PRE4P2_KIT_DisCha-Dall_80K.xlsx". Since 5 bar is the lowest pressure level investigated in the tests, the respective data columns can be found in the first seven columns (columns A to G) of the sheet. A screenshot of this sheet is shown in Figure 9.

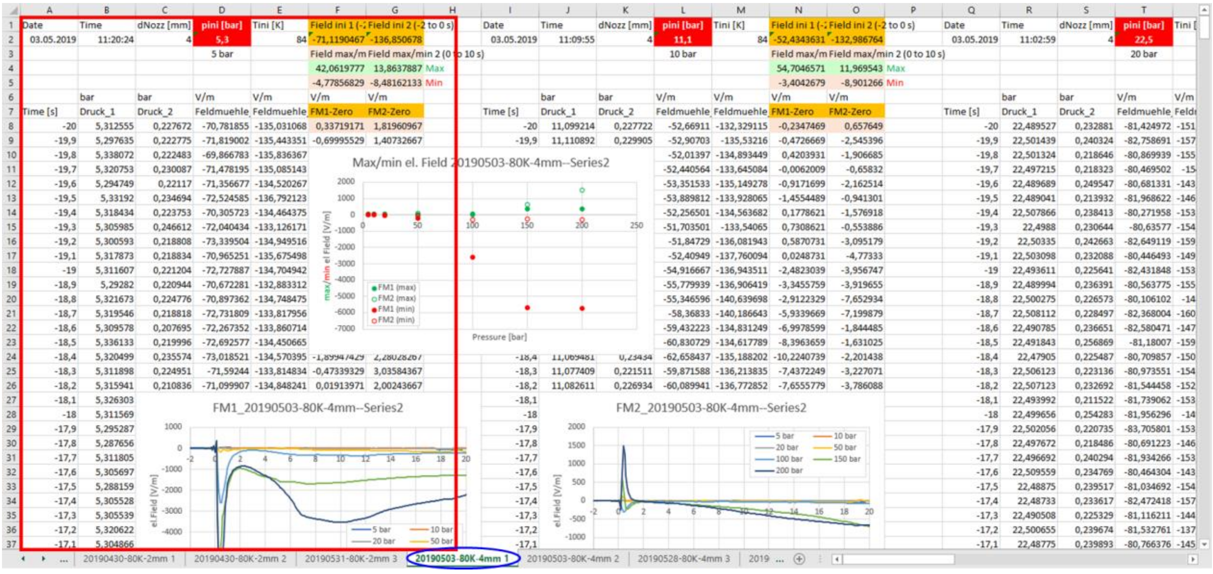


Figure 9: Screenshot of data sheet "20190503-80K-4mm 1" (blue circle) with columns for experiment "20190503_112024" (red rectangle).

For every dataset of one experiment 7 columns are used in the Excel-worksheet. On the sheet the datasets of several experiments are arranged next to each other from left to right in the order of increasing nominal initial pressure. If an experiment at a given initial pressure value is missing in the series, the respective columns are left empty, so that the data for experiments with the same initial pressures can be found in the same columns of every sheet. In the upper two lines of the first 5 columns of a dataset the initial conditions of the experiment are summarized (date, time, nozzle-diameter, initial pressure and temperature). In the lower part of these columns the data for this experiment is listed. The first column is the synchronized time, which is the time that elapsed after the first increase is observed in the record of the pressure sensor in the release nozzle. The following two columns contain the pressure values measured during the experiment in the vessel and the nozzle, respectively, and the next two columns contain the measured values of the two field mills that were used in the DisCha experiments. Every dataset begins 10 s prior to the first pressure increase in the release nozzle and ends at the end of the raw data record. If the data starts later in the raw data of an experiment, the corresponding lines at the top of the dataset are left empty, so that a given line number corresponds to the same time in all datasets.

The last two columns of a dataset contain the offset-corrected field data. For the correction the mean value measured by a field mill during the last 2 s prior to the beginning of the release is calculated in line 2. Then, as for example in experiment “20190503_112024”, the mean values calculated in the cells F2 and G2 are subtracted from the raw data values of the columns D and E and the result, which is the offset-corrected field value, is displayed in the columns F and G. In the cells F4 and G4 the maximum offset-corrected field values for the first 10 s after the beginning of the release are calculated, and in the cells F5 and G5 the corresponding minimum values are shown. These max/min values for all experiments of a series are collected once again at the far-right end of the sheet and plotted in the top graph at the left end of the sheet (see Figure 9) as a function of the initial pressure. In the lower graphs the signal courses of the field mills during the first 20 s and 4 s after the beginning of the release for all experiments of the series are shown (left graphs: field mill 1, right graphs: field mill 2).

The first sheet in both Excel-files is an additional summary sheet, where the max/min data as well as the initial conditions of all experiments of this file are summarized (Figure 10). Here the max/min values of all series with a given nozzle diameter are plotted in one graph over the initial pressure in different representations to allow a fast overview over the results of the different series with different nozzle diameters.

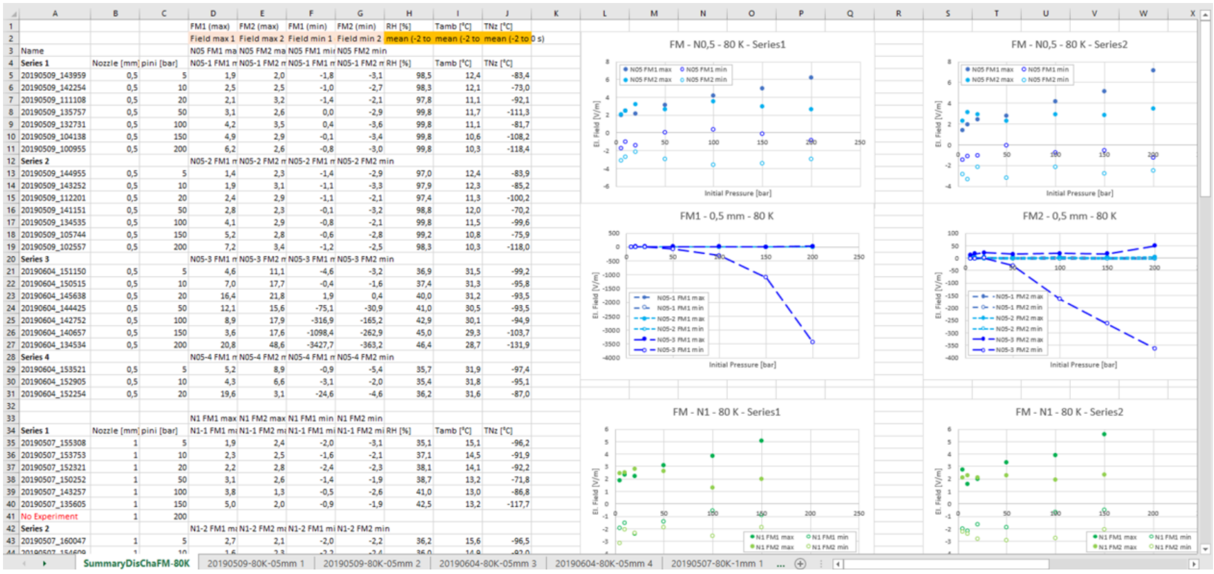


Figure 10: Screenshot of the summary sheet of Excel file “PRE4P2_KIT_DisCha-Dall_80K.xlsx”.

5.2 Cryostat Datasets explained with Cold Case 20200521_113404

All experimental data of the Cryostat tests (see Table 4) are published as Microsoft Excel-files via the PRESLHY repository on KITopen[1], separately for the ambient (referring to the left part of Table 4 and labeled “290K”) and the cryogenic (referring to the right part of Table 4 and labeled “30K”) hydrogen temperatures. Due to the limited number of experiments one data sheet per nozzle diameter is sufficient to contain all datasets of the experiments at the respective temperature.

So, for example the cold case experiment with the 4 mm nozzle that was conducted the 21st of May 2020 at 11:34 am at an initial pressure level of 4.6 bar bears the name “20200521_113404” and can be found as last entry of the far-right column in the middle part of Table 4. According to the color scheme and the bottom lines of the table the data of this experiment can be found in the sheet “20200521-30K 4mm” of Excel file “PRE4P2_KIT_Cyostat-Dall_30K.xlsx”. Since the initial pressure of the experiment was the highest initial pressure of the series this data can be found as last dataset at the right end of the sheet, just in front of the summary of the max/min-values of all experiments of this sheet (see Figure 11).

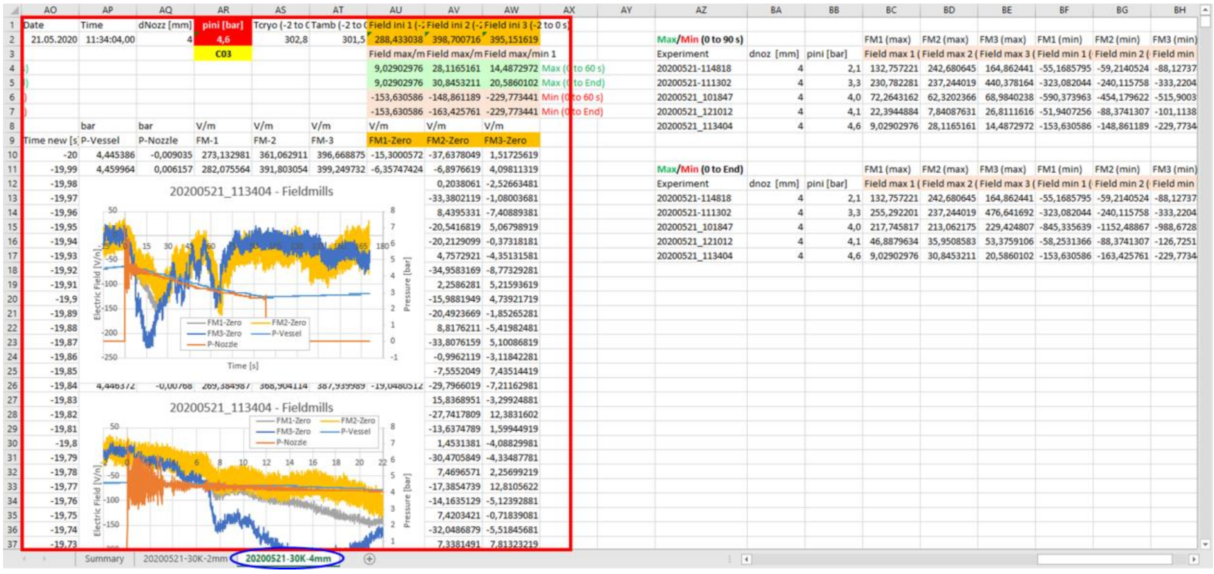
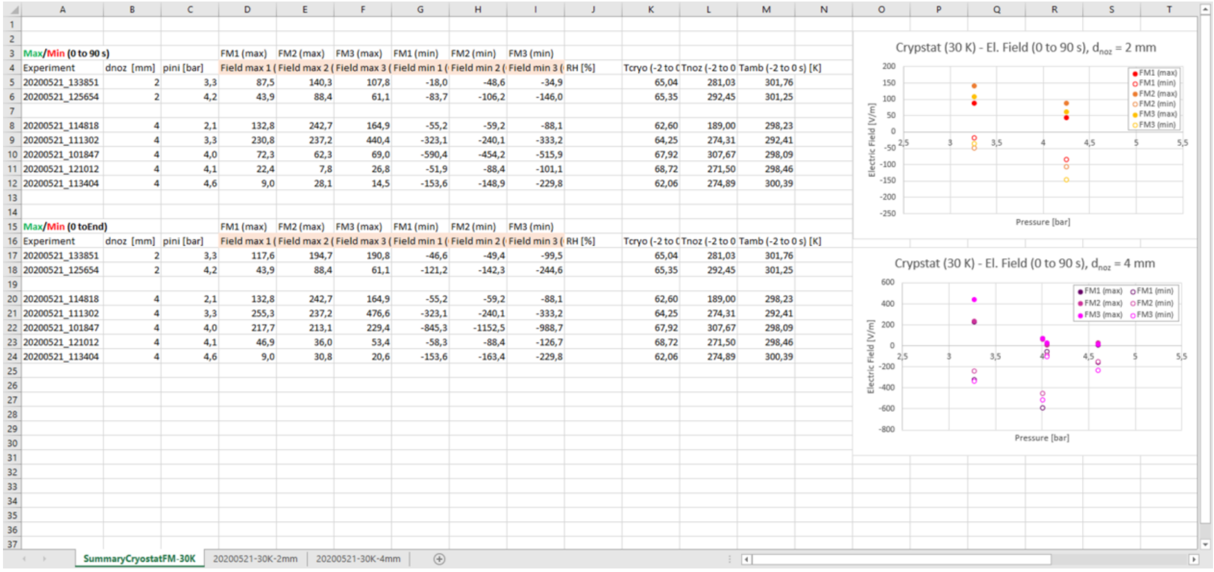


Figure 11: Screenshot of data sheet “20200521-30K-4mm” (blue circle) with columns for experiment “20200521_113404” (red rectangle) and summary of min/max-values (right).

The main difference in the contents of the sheets compared to the DisCha-experiments is, that in this experimental series 3 field mills were used and thus 9 columns are needed to host the selected data of one experiment (1 x time, 2 x pressure, 3 x field mill raw, 3 x field mill offset-corrected). Another difference is that every experiment has own plots showing the respective data since summarizing plots of the records proved to be not expressive.

Summarizing plots of the min/max-values of the offset-corrected field measurements are shown in the additional summary sheet of both Excel-files (first sheet in both files). Here also the initial conditions of all experiments in the file are included (Figure 12).

[1] https://doi.org/10.5445/IR/1000096833



Max/Min (0 to 90 s)			FM1 (max)	FM2 (max)	FM3 (max)	FM1 (min)	FM2 (min)	FM3 (min)				
Experiment	dnoz [mm]	pini [bar]	Field max 1 (	Field max 2 (	Field max 3 (	Field min 1 (	Field min 2 (	Field min 3 (	RH [%]	Tcryo (-2 to (	Tnoz (-2 to 0	Tamb (-2 to 0 s) [K]
20200521_133851	2	3,3	87,5	140,3	107,8	-18,0	-48,6	-34,9		65,04	281,03	301,76
20200521_125654	2	4,2	43,9	88,4	61,1	-83,7	-106,2	-146,0		65,35	292,45	301,25
20200521_114818	4	2,1	132,8	242,7	164,9	-55,2	-59,2	-88,1		62,60	189,00	298,23
20200521_111302	4	3,3	230,8	237,2	440,4	-323,1	-240,1	-333,2		64,25	274,31	292,41
20200521_101847	4	4,0	72,3	62,3	69,0	-590,4	-454,2	-515,9		67,92	307,67	298,09
20200521_121012	4	4,1	22,4	7,8	26,8	-51,9	-88,4	-101,1		68,72	271,50	298,46
20200521_113404	4	4,6	9,0	28,1	14,5	-153,6	-148,9	-229,8		62,06	274,89	300,39

Max/Min (0 toEnd)			FM1 (max)	FM2 (max)	FM3 (max)	FM1 (min)	FM2 (min)	FM3 (min)				
Experiment	dnoz [mm]	pini [bar]	Field max 1 (	Field max 2 (	Field max 3 (	Field min 1 (	Field min 2 (	Field min 3 (	RH [%]	Tcryo (-2 to (	Tnoz (-2 to 0	Tamb (-2 to 0 s) [K]
20200521_133851	2	3,3	117,6	194,7	190,8	-46,6	-49,4	-99,5		65,04	281,03	301,76
20200521_125654	2	4,2	43,9	88,4	61,1	-121,2	-142,3	-244,6		65,35	292,45	301,25
20200521_114818	4	2,1	132,8	242,7	164,9	-55,2	-59,2	-88,1		62,60	189,00	298,23
20200521_111302	4	3,3	255,3	237,2	476,6	-323,1	-240,1	-333,2		64,25	274,31	292,41
20200521_101847	4	4,0	217,7	213,1	229,4	-845,3	-1152,5	-988,7		67,92	307,67	298,09
20200521_121012	4	4,1	46,9	36,0	53,4	-58,3	-88,4	-126,7		68,72	271,50	298,46
20200521_113404	4	4,6	9,0	30,8	20,6	-153,6	-163,4	-229,8		62,06	274,89	300,39

Figure 12: Screenshot of the summary sheet of Excel file "PRE4P2_KIT_Cyostat-Dall_30K.xlsx".

6 Short Summary of Results

6.1 DisCha-Experiments with Field Mills

In the frame of the E3.1 Part A test series of the PRESLHY project 214 hydrogen blow-down experiments were made and evaluated using the DisCha-facility of KIT. 88 of the experiments were made at cryogenic temperatures, close to the standard boiling temperature of nitrogen (approximately 80 K) and 126 at ambient temperature (approximately 300 K). For 123 of the 214 experiments, electrostatic measurements with two field mills were conducted. Those experiments are part of the experimental series E4.2.

The inventories stored in the DisCha pressure vessel for those blow-down experiments vary from about 1,2 g, for the lowest pressure 5 bar and ambient temperature, to about 140 g, for the highest pressure 200 bar and standard boiling temperature of nitrogen. Table 5 contains the densities for the relevant conditions and the corresponding inventories in the DisCha vessel with 2.815 dm^3 free volume. The densities have been derived with real gas factors extracted from [2].

Table 5: Hydrogen inventories of the DisCha experiments

Temperature / K	Pressure / bar	1	5	10	20	50	100	150	200
293,15	Ideal Density / (g/l)	0,083	0,414	0,827	1,654	4,136	8,271	12,407	16,542
	Z -factor @ 300 K	1,000	1,000	1,008	1,013	1,030	1,060	1,090	1,120
	Density / (g/l)	0,083	**0,414**	**0,821**	**1,633**	**4,015**	**7,803**	**11,382**	**14,770**
	H2 mass in DisCha / g	0,233	**1,164**	**2,310**	**4,597**	**11,303**	**21,966**	**32,042**	**41,578**
77	Ideal Density / (g/l)	0,315	1,574	3,149	6,298	15,745	31,490	47,235	62,980
	Z -factor @ 80K	1,000	0,990	0,980	0,970	0,960	1,020	1,130	1,260
	Density / (g/l)	0,315	**1,590**	**3,213**	**6,493**	**16,401**	**30,872**	**41,801**	**49,984**
	H2 mass in DisCha / g	0,886	**4,477**	**9,045**	**18,277**	**46,169**	**86,906**	**117,669**	**140,704**

All experiments with identical temperature, pressure and nozzle diameter combination have been repeated at least three times. The test series with 4 mm nozzle at ambient temperature with a pressure of 100 bar provide 8 and the 200 bar 7 repetitions and allow for a statistical evaluation of the measured reservoir pressure. The root-mean-square deviation (RMSD) for the two test series was calculated and for 100 bar it is less than +/- 0.5%. For 200 bar it is about +/- 1%. Figure 13 qualitatively demonstrates the good reproducibility of the experiments by plotting all 7 curves and their averages in an overlay mode in the same diagram.

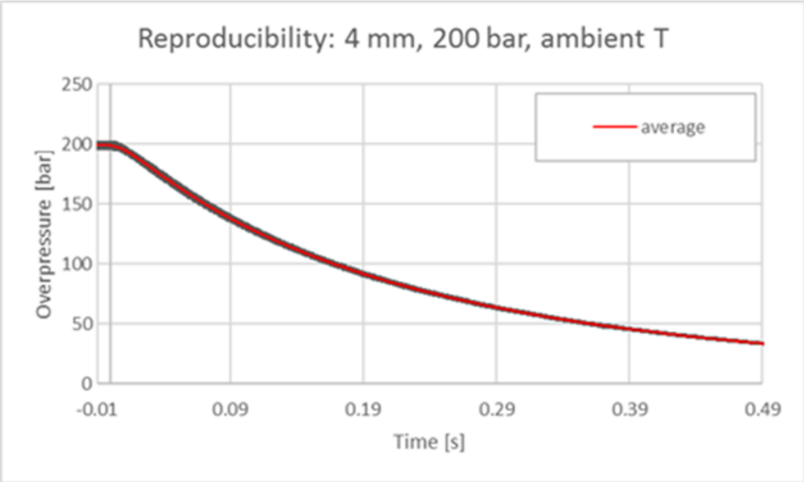


Figure 13: Qualitative demonstration of the reproducibility of the 200 bar blow-down experiments of hydrogen with ambient temperature (RMSD of vessel overpressure 1%)

The observations with respect to the electrostatic field generated by the jet releases are summarised in the following.

Strong electrostatic fields (~6000 V/m) have been observed for the 80 K cold releases. They are typically 100 times larger than the fields measured for corresponding releases at ambient temperature (compare Figure 14 and Figure 16). The signal at field mill FM1 close to the release point is always stronger than the signal recorded at FM2 at a larger distance. Although the signal shows initially synchronous behaviour, the direction of the field vector is opposite, see Figure 14 and Figure 15. Both figures also show that in general the maximum field strength increases with the storage pressure.

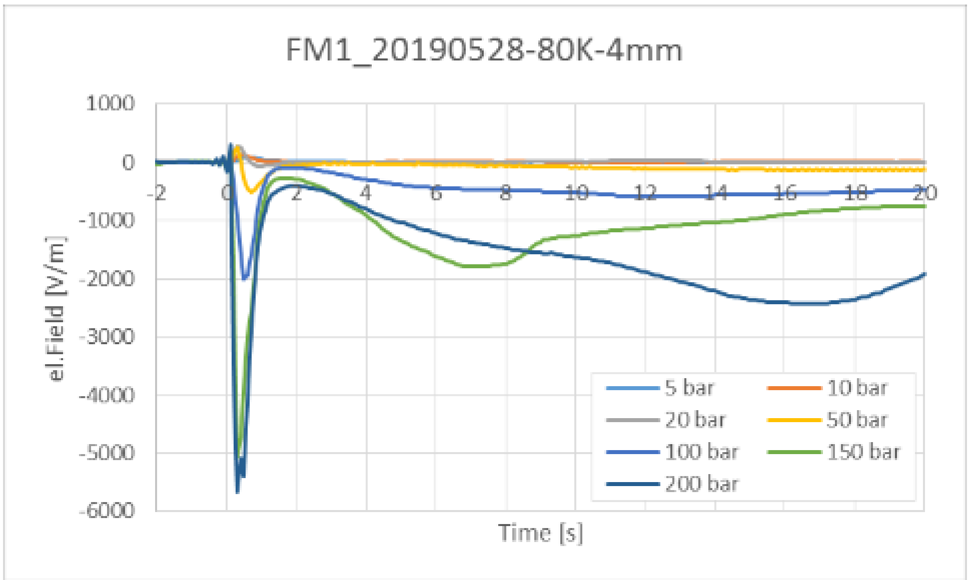


Figure 14: Electrostatic field measured with field mill FM1 for blow-down of up to 200 bar hydrogen at standard nitrogen boiling temperature.

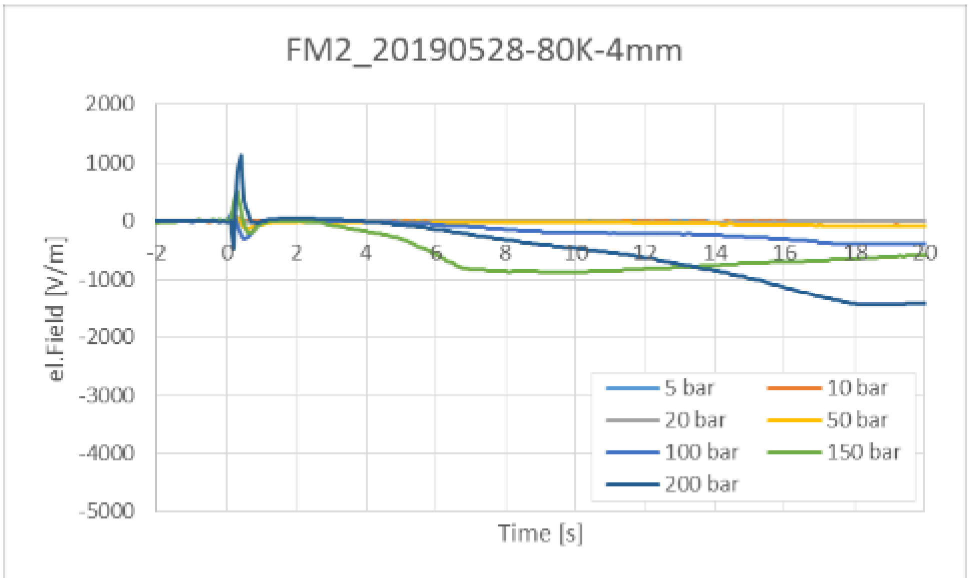


Figure 151: Electrostatic field measured with field mill FM2 for blow-down of up to 200 bar hydrogen at standard nitrogen boiling temperature

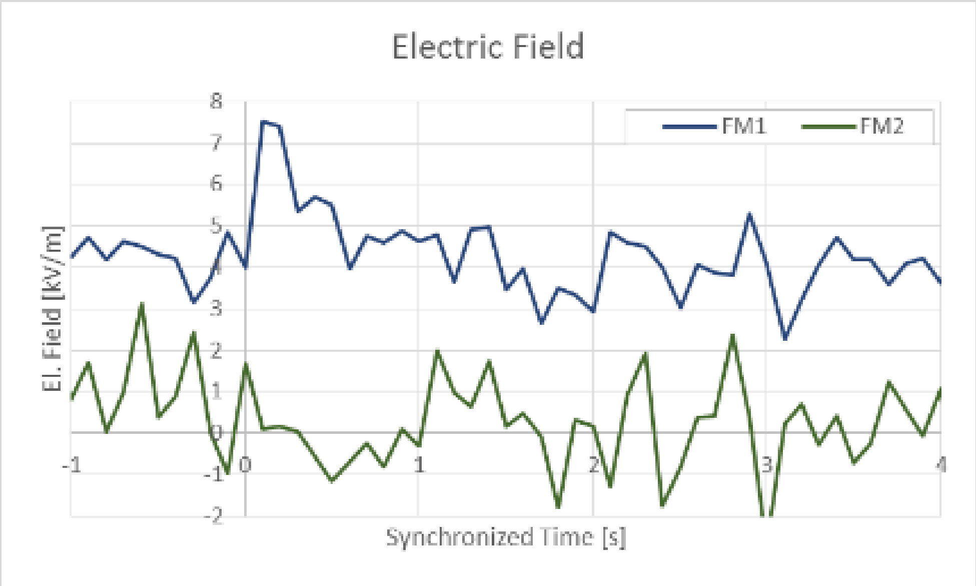


Figure 16: Electrostatic field measured with field mills FM1 and FM2 for blow-down of 200 bar hydrogen via 4mm nozzle, starting from ambient temperature (20190523_113015)

Figure 20 gives an overview over the measurements of the complete experimental series with the 4 mm nozzle at an initial temperature of 80 K in the reservoir already shown in Figure 14 and Figure 15. In the graph the max/min-values of the electrostatic field measurements are plotted over the initial pressure in the reservoir. The figure again demonstrates that the direction of the field measured by the field mills might be opposite, and that the intensity of the signal is stronger in the record of field mill FM1 which is positioned closer to the release nozzle than FM2.

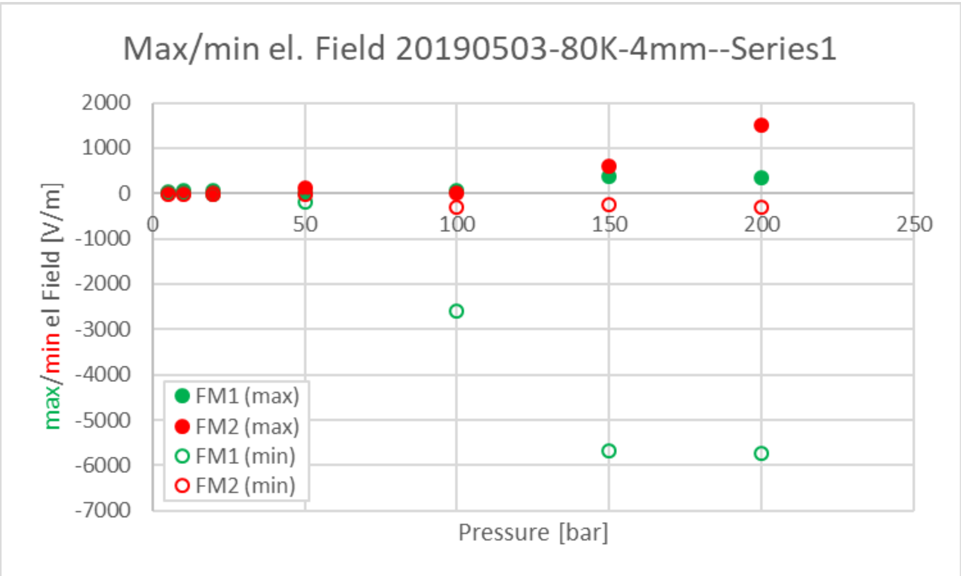


Figure 17: Maximum and minimum electrostatic field strength measured at field mill FM1 and FM2 for pressures from 5 to 200 bar with a starting temperature of 80 K in the pressure reservoir.

Despite the relatively high electrostatic fields observed in the experiments with the DisCha-facility no spontaneous ignition of the released jet has been observed. This concerns all discharge tests of E3.1A (more than 200) and not only those constituting the test series E4.2.

6.2 Cryostat-Experiments

With the Cryostat-facility 12 release experiments were performed for WP3.1b, of which 7 tests were conducted with liquid hydrogen (LH2), while the remaining 5 tests were reference tests with gaseous hydrogen at ambient temperature. In all experiments three field mills were used.

Due to the specifications of the cryostat vessel (pmax = 6 bar) the test matrix was limited to pressures of 5 bar(abs.). Nevertheless, rather high H2-inventories of up to 3.78 kg were reached due to the large volume of the cryostat (Vcryostat = 225 dm³) and the relatively high density of LH2 (ρLH2 = 70.79 kg/m³) compared to gaseous hydrogen (GH2, ρGH2 = 0,0899 kg/m³) at ambient temperature. In the experiments a release of LH2 was reached after a certain cool-down time during which the release branch from the vessel to the nozzle was brought to cryogenic temperature. Due to the large inventory and the nozzles used (2 mm and 4 mm open diameter) the experiments were rather long.

During the first tens of seconds usually strong changes in the field strength were observed. The field values were mostly considerably higher during the release of LH2 compared to the DisCha-experiments at 80 K with gaseous hydrogen at pressures of 5 bar. But in contrast to the DisCha-experiments the field values seem to decrease with increasing initial pressure level, but the pressure range investigated (2 to 5 bar) is rather small (Figure 18).

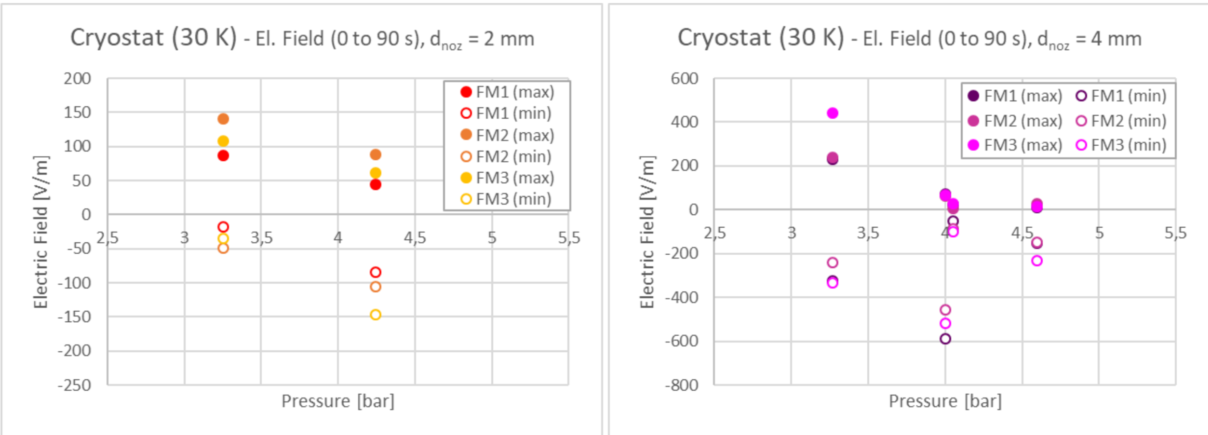


Figure 18: Maximum and minimum electrostatic field strength measured at the three field mills with the Cryostat-facility during the first 90 s of the LH2-releases.

In some cases, especially for the LH2-releases, strong fluctuations of the field values were also observed much later. These fluctuations might be caused by environmental influences, since the Cryostat facility was operated unprotected in free field. Another reason might be finger-like structures that formed at the tip of the nozzle during the release (Figure 19). These structures, most likely formed of solidified air components, were blown away from time to time or just fell down due to their weight. But a correlation between the removal of the structures and strong field fluctuations is not yet fully evaluated.

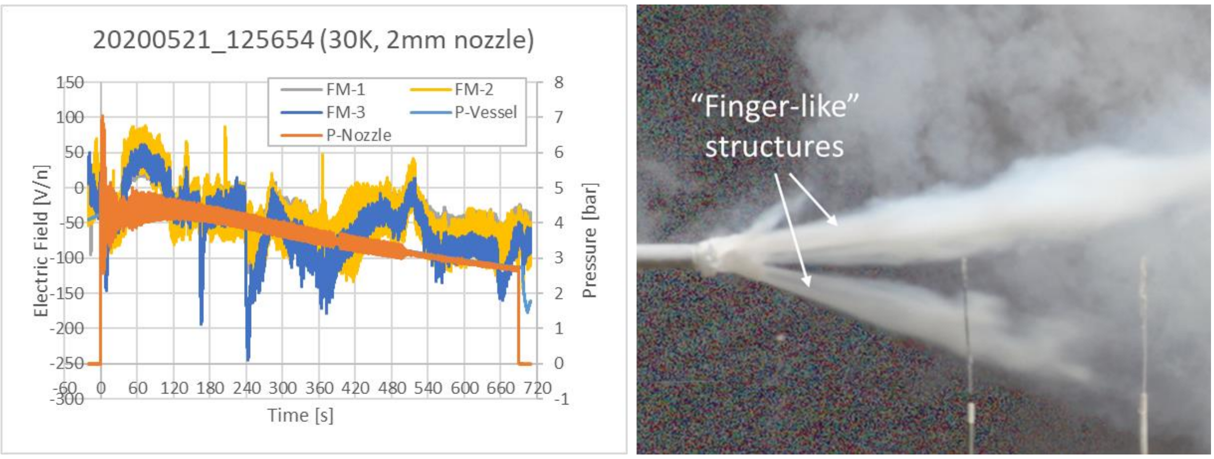


Figure 19: Pressure and field mill records measured with the Cryostat-facility during a LH2-release through the 2 mm nozzle (left): Strong fluctuations of the field strength were observed sporadically during the complete release. Photo of the "finger-like" structures that formed at the tip of the nozzle during this experiment (right)

7 Summary, Conclusions and Outlook

In the frame of the PRESLHY project more than 200 hydrogen blow-down experiments were made with the DisCha-facility at KIT, about half of them were made at ambient temperature, the other half at cryogenic temperatures, approximately 80 K. The reservoir pressure has been varied from 5 to 200 bar, the tested release nozzle diameter was 0.5, 1, 2 and 4 mm.

In total 12 experiments with the Cryostat-facility were performed for WP3.1b of the PRESLHY project. 5 of these experiments were done with gaseous H2 at ambient temperature as a reference while in the remaining 7 tests liquid hydrogen releases through nozzles with diameters of 2 and 4 mm were realized. Due to the specifications of the cryostat vessel the storage pressure was limited to 5 bar, but nevertheless high inventories of up to 3.78 kg H2 were reached.

Extensive equipment was used to measure hydrogen mass, pressure and temperature in the pressure vessels and temperature, hydrogen concentration and electrostatic field in and around the released jets. Additionally, all ambient conditions, like temperature, pressure and relative humidity have been recorded.

The DisCha-tests starting from a reservoir temperature of about 80K showed relative high electrostatic fields generated, especially for high initial pressure levels. Supported by some precursor tests it is assumed that the generation of the electrostatic field is associated with ice crystals formed on the release nozzle before the actual release and with breaking of this ice crystal and sub-sequent entrainment during the initial phase of the gas discharge.

The fields measured with the Cryostat-facility during the release of LH2 mostly were considerably higher than the ones measured in the DisCha-experiments at 80 K with pressures of 5 bar. But in contrast to the DisCha-experiments the field values seem to decrease with increasing initial pressure level, but the pressure range investigated (2 to 5 bar) is rather small.

The results of the experiments on electrostatics might be used for the development of an empirical model for the electrostatic charge generation. The releases of LH2 in the Cryostat-facility examine the two-phase effects of the discharge at moderate pressures up to 5 bar. This pressure is the low end of the initial pressures applied in the DisCha-facility and therefore there is a good opportunity for comparing and linking the outcomes of the two series of experiments.

8 References

[1] KITopen, public research data repository; link for datasets and this report: https://doi.org/10.5445/IR/1000096833

[2] McCarty, R.D., Hord, J., and Roder, H.M. Selected properties of hydrogen (engineering design data). Final report. United States: N. p., 1981. Web.