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To cite this article: A Janzen *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **278** 012077

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Experimental validation of a self-calibrating cryogenic mass flowmeter

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Abstract. The Karlsruhe Institute of Technology (KIT) and the WEKA AG jointly develop a commercial flowmeter for application in helium cryostats. The flowmeter functions according to a new thermal measurement principle that eliminates all systematic uncertainties and enables self-calibration during real operation. Ideally, the resulting uncertainty of the measured flow rate is only dependent on signal noises, which are typically very small with regard to the measured value. Under real operating conditions, cryoplant-dependent flow rate fluctuations induce an additional uncertainty, which follows from the sensitivity of the method. This paper presents experimental results with helium at temperatures between 30 and 70 K and flow rates in the range of 4 to 12 g/s. The experiments were carried out in a control cryostat of the 2 kW helium refrigerator of the TOSKA test facility at KIT. Inside the cryostat, the new flowmeter was installed in series with a Venturi tube that was used for reference measurements. The measurement results demonstrate the self-calibration capability during real cryoplant operation. The influences of temperature and flow rate fluctuations on the self-calibration uncertainty are discussed.

1. Introduction

Flowmeters represent a vital element of process monitoring and control in almost every process engineering application. For temperatures close to ambient, numerous flowmeters based on various measurement principles are available. For cryogenic helium applications, however, no standard flowmeter apart from a specially designed Coriolis [1] exists [2]. The reason is that all measurement principles use empirical correlations to relate the measured quantity to the flow rate. A factory calibration, typically performed at room temperature with air or nitrogen, is therefore indispensable. Its validity is restricted close to the calibration conditions and hence, the use at cryogenic temperatures results in an additional measurement uncertainty. A factory calibration under real operating conditions is usually unfeasible in terms of effort and cost [2]. A new thermal flow measurement principle, developed at KIT [2, 3] overcomes this problem by its ability of self-calibration at any time and under

real cryoplant operation. Based on this new principle, KIT and WEKA AG, Switzerland, jointly develop a commercial flowmeter for cryogenic helium applications.

The new principle is shortly introduced in Section 2. Section 3 describes a prototype measurement system and its installation inside a cryostat of the TOSKA test facility. The presentation and discussion of experimental results under different cryogenic temperatures follows in Section 4. The final Section draws the conclusion and gives an outlook on the further development of the commercial flowmeter.

2. The new thermal flow measurement principle

This chapter gives a short overview of the new thermal measurement principle. Detailed descriptions of the self-calibration procedure and the requirements for the flowmeter design are given in [2]. Figure 1 shows at the lower left corner a schematic flowmeter that works according to the new principle. The flowmeter is equipped with a heat exchanger that enables variable heat loads $\dot{Q}$. By design, the heat exchanger has a nearly constant surface temperature (T_A) in flow direction, which is measured by a temperature sensor. Additionally, the fluid's temperature is measured up- and downstream of the heater (T' and T''). By taking into account T_A, this readings are reduced to a inlet and outlet temperature difference ($\Delta T'$ and $\Delta T''$) for further evaluation. [2]

The diagrams in Figure 1 schematically represent the function of the measurement principle. The ability of self-calibration is based on two analytic expressions, which use $\dot{Q}$, $\Delta T'$ and $\Delta T''$ as input parameters. The first expression ($\dot{m}_A$) is derived from the fluid's energy balance. Its combination with the heat transfer kinetics yields the second evaluation function ($\dot{m}_B$). In this second expressions, the overall thermal resistance R is an unknown quantity that cannot be precisely calculated. However, an experimental determination is possible by ramping the heat load at constant mass flow rate (top left corner in Figure 1). From the different measured temperature differences, logarithmic mean temperatures $\Delta T_{\mathrm{LM},i=1\ldots4}$ can be calculated and R is found as the slope of a linear fit (center bottom). [2]

Under real measurement conditions, the readings of $\dot{Q}_i$, $\Delta T_i'$ and $\Delta T_i''$ are always error-prone. Especially the systematic uncertainties result in large deviations among the calculated mass flow rates $\dot{m}_{A,i}$ and $\dot{m}_{B,i}$ that can easily reach plus-minus several hundred percent (center top in Figure 1).

In the case of error-free parameters, the results of $\dot{m}_{A,i}$ and $\dot{m}_{B,i}$ must be identical as both equations are analytical and use the same input quantities. This fact can be used in a minimization algorithm,
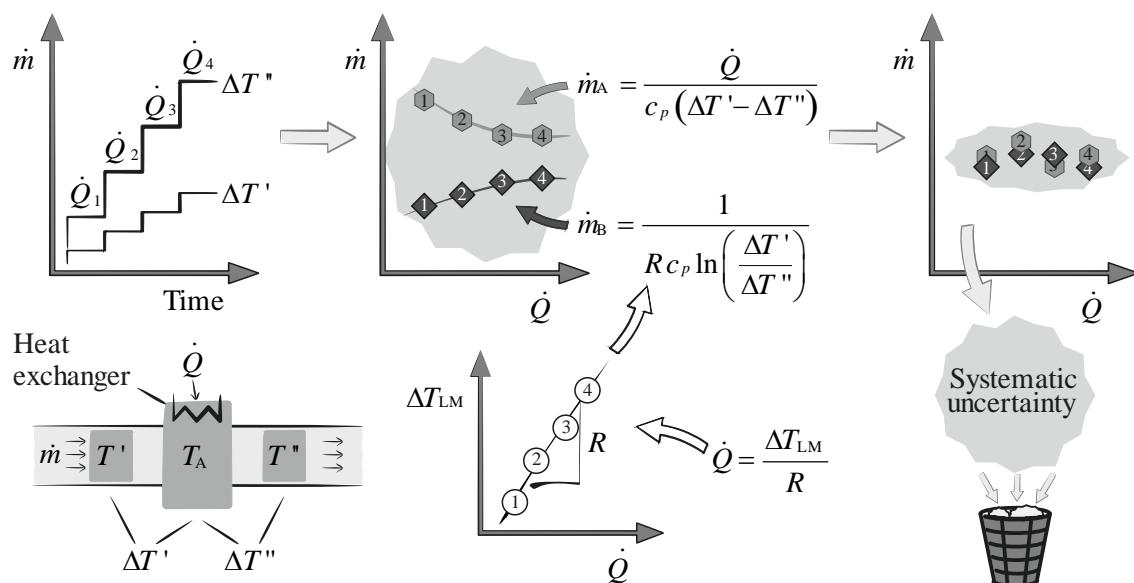

Figure 1. Schematic flowmeter and representation of the self-calibration procedure in accordance to [2, 3].
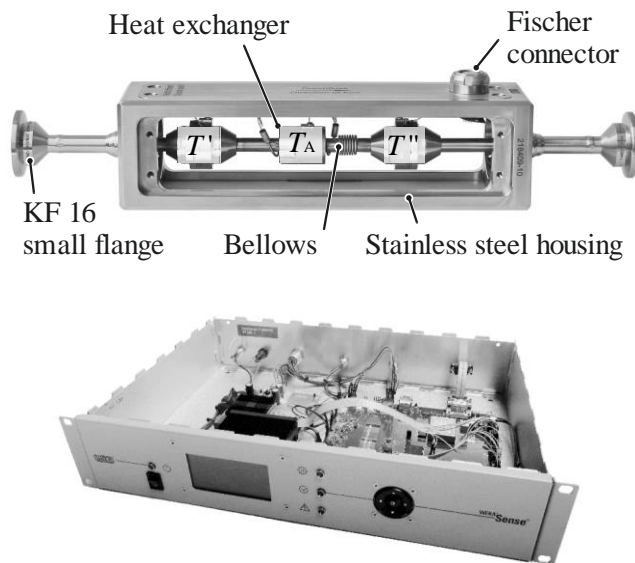
Figure 2. Photo of a prototype flowmeter with open stainless steel housing (top) and photo of the developed electronics installed in a 19" housing with open cover (bottom).
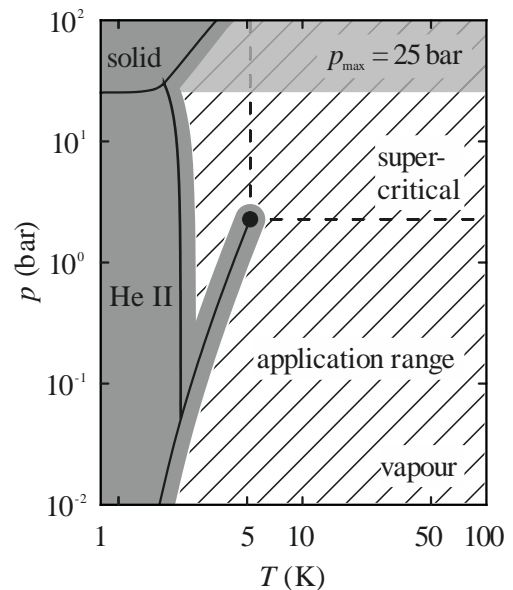
Figure 3. Schematic representation of the flowmeter's application range in a pressure-temperature plot for ^{4}He with data from HEPAK [4].

which minimizes the flow rate deviations by variation of the systematic uncertainties of the measured quantities. The three measured quantities ($\dot{Q}$, $\Delta T'$, $\Delta T''$) are corrected by these systematic uncertainties for the flow rate calculation. The result of this self-calibration procedure is a mass flow rate – averaged over the ramping time with eight values in total ($\dot{m}_{A,i=1...4}$ and $\dot{m}_{B,i=1...4}$), which is free of any systematic uncertainty and only dependent on signal noises. Typically, the signal noises are very small compared to the measured value. The overall measurement uncertainty of the self-calibration procedure is evaluated in terms of the standard deviation resulting from the eight mass flow rates. Under real operating conditions, cryoplant-dependent flow rate fluctuations increase this standard deviation and therefore contribute to an additional uncertainty.

3. Experimental setup

The experimental investigations were conducted with a prototype flowmeter (cf. Figure 2) manufactured by WEKA AG. Its design corresponds essentially to the description in Section 2. The fluid flows through a thin-walled tube with an inner diameter of 6 mm. Downstream, a bellows compensates for thermal stress during cool-down and warm-up of the cryogenic system. The heat exchanger consists of a mineral insulated resistive heating element embedded in a copper cylinder that is directly brazed onto the measurement tube. One of three calibrated Cernox^{TM} type CX-1050-SD-HT-1.4L temperature sensors is placed on the heater surface. Another two Cernox^{TM} sensors are used for the measurement of the up- and downstream fluid temperatures. The measurement is performed on the outside of the tube with the aid of specially designed copper elements. These mixing elements enable a mean fluid temperature measurement over the whole cross section. Any possible temperature offset from the thermodynamic mean temperature represents a systematic offset, which is fully compensated by the self-calibration procedure.

The flowmeter is embedded in a stainless steel housing to absorb mechanical loads and to shield direct thermal radiation. During the design process, special attention was drawn to the vacuum compatibility and a compact design. The resulting dimensions of the flowmeter (total length: 280 mm, height and depth: 50 mm) facilitate space-saving integration into cryostats or cryogenic transfer lines.
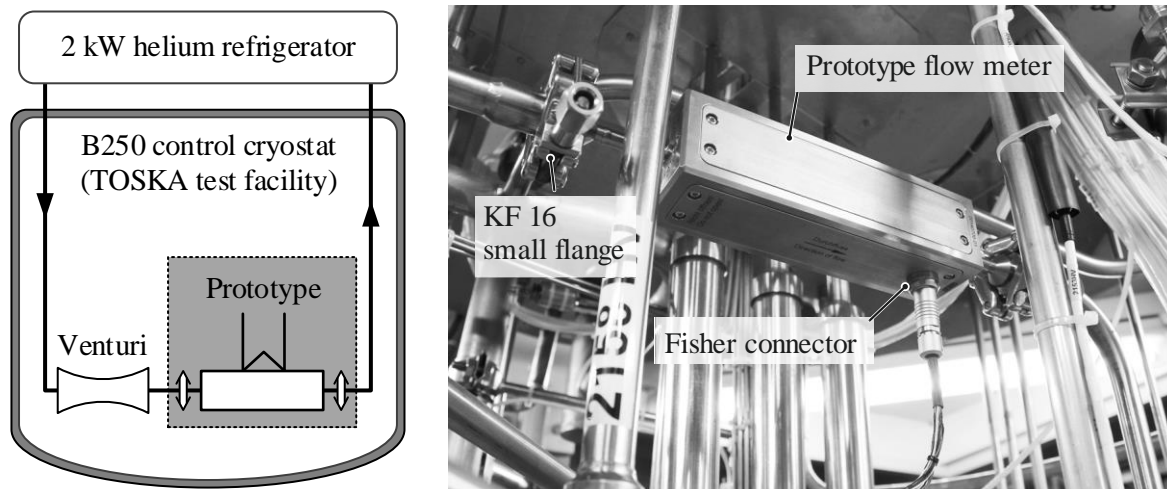
Figure 4. Schematic representation of the experimental setup (left) and photo of the installation within the B250 control cryostat (right).

On top of the housing, all electrical connections are lead through a Fischer connector. All connections are thermally anchored at the housing and use four-wire sensing with twisted pairs of cryogenic wire. From the Fischer connector one cable is needed to connect the flowmeter to the electronics at room temperature. The electronics is a KIT-internal development, which combines the heater control and the temperature sensors with the automated measurement and evaluation procedure of the self-calibration[1]. All electronic components are installed into a 19" housing (cf. Figure 2). The electronics can be either integrated in a control rack / cabinet or used as a stand-alone unit. It is equipped with serial interfaces (RS-232 and RS-486) and an analogue output for the mass flow rate.

Figure 3 shows the application range of the flowmeter for helium applications (hatched area). Due to the thermal principle, flow measurement is only applicable in the single-phase fluid states of helium (liquid, vapour or supercritical). Though the heat input and the pressure drop of the flowmeter are very small, the risk of first-order phase change or the occurrence of metastable fluid states exists close to the saturation lines. Therefore, those areas as well as He II are excluded by principle (dark grey shaded areas). The indicated application range covers the most common requirements in helium systems. For the prototype sensor, a nominal design pressure of 25 bar has been chosen (light grey shaded area) with a mass flow range of 0.2 to 12 g/s.

The experimental investigations were carried out within the TOSKA test facility at KIT [5]. As schematically shown in Figure 4, the prototype flowmeter was installed in a control cryostat (B 250) that is connected to a 2 kW helium refrigerator. The flowmeter was installed in series with an existing Venturi tube that was used for reference measurements. It is designed for flow rates up to 60 g/s.

4. Experimental results and discussion

4.1. Measurement conditions
The flowmeter's ability of self-calibration was tested at c. 30, 50 and 70 K and absolute pressures in the range of 1.6 to 5.6 bar. The flow rates were varied from about 4 to 12 g/s. Table 1 gives an overview of the resulting fluid states at the different temperatures and the respective numbers of self-calibration points.

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[1] For the experimental investigations shown in Section 4, the data evaluation was not yet implemented and therefore executed on a computer externally. Due to the manual control of the self-calibration procedure, more than the typical time of two minutes for a run with a fully automated measurement system was required.

Table 1. Overview of the measurement conditions.

Temperature (K)	Fluid state	Self-calibration points
30	supercritical	3
30	vapour	1
50	supercritical	8
50	vapour	2
70	supercritical	7
70	vapour	1

4.2. Results

Figure 5 shows a comparison of the flow rates of the prototype flowmeter ($\dot{m}_{\text{Prototype}}$) and the Venturi tube ($\dot{m}_{\text{Venturi}}$). The uncertainty of the new flowmeter is a direct result of the self-calibration (cf. Section 2). The Venturi tube's mass flow rate is a mean value averaged over the time period of a self-calibration run. Its uncertainty is calculated according to the guide to the expression of uncertainty in measurement (GUM) using Type A and Type B contributions [6]. For the Type B uncertainty, a value of 3.2 % of the reading with a coverage factor of $k = 2$ is used according to [7]. The Type A uncertainty is calculated from the standard deviation of the Venturi readings divided by the square root of the number of readings (~ 3 values per minute).

For complete agreement of the two measurement principles within their uncertainties, all measured points should be positioned on the angle bisector of the diagram shown in Figure 5. The results reveal a very satisfactory overall agreement. As expected, the fluid state (filled: sub-critical gaseous He, unfilled: supercritical He) has no influence on the self-calibration. For Venturi mass flow rates below 5 g/s, the self-calibration results slightly exceed the Venturi readings by about 10 to 18 %. A precise statement on the cause of this deviation is not possible, as the Venturi tube is operated far below its design flow rate of 60 g/s. The typical turndown ratio of about 3 : 1 ($\dot{m}_{\text{Venturi, turndown}} = 60...20$ g/s) [8] is largely exceeded by a factor of up to five ($\dot{m}_{\text{Venturi, exp}} = 12...4$ g/s). The impacts on the measurement uncertainty due to this low flow operation are difficult to quantify. Nevertheless, it is likely that the Type B uncertainty increases to values beyond 3.2 %, yielding again a good agreement of the results.

From the experimental results, it can be concluded that the new measurement principle's ability of self-calibration works during real cryoplant operation. It must be pointed out that the prototype flowmeter was directly installed into the cryostat, without any prior flow calibration. The new flowmeter has no need for a comparative calibration against a standard. In fact, it may be considered as an "industrial primary standard" itself. This is a new and extraordinary feature in flow measurement.

4.3. Influence of temperature and flow rate fluctuations during self-calibration

Under real cryogenic operating conditions, the flowmeter faces fluctuations in temperature and flow rate. Therefore, it is important to understand how these fluctuations affect the self-calibration procedure.

Figure 6 a exemplarily shows the raw inlet and outlet temperature profiles (readings of T' and T'') of one self-calibration run at 30 K with supercritical He. During this run, overall temperature fluctuations of 390 mK occurred (max-min fluctuation), which equally affected T' and T''. Due to these fluctuations, the temperature increase in T'' caused by $\dot{Q}$ is hardly distinguishable, especially at low heat loads. For the flow evaluation, however, only the *fluid's temperature difference* ($\Delta T_{\text{F}} = \Delta T' - \Delta T'' = T'' - T'$) is important. This cancels out the temperature fluctuations and ΔT_{F} is not affected (cf. Figure 6 b). For this measurement, the calibrated flow rate is $\dot{m}_{\text{Prototype}} = (11.8 \pm 0.11)$ g/s ($k = 2$). The induced temperature increase from 36 mK ($\dot{Q}_1 = 2$ W in step 1) to 158 mK ($\dot{Q}_4 = 9.7$ W in step 4) is significantly lower than the temperature fluctuation. The relative measurement uncertainty is only 0.97 % of the measured value. This clearly indicates that temperature fluctuations do not influence
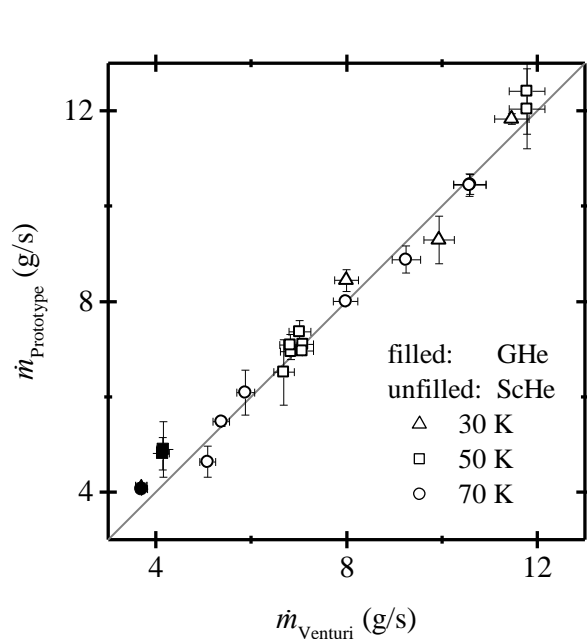
Figure 5. Comparison of the measured mass flow rates of the prototype flowmeter and the Venturi tube at different temperatures.
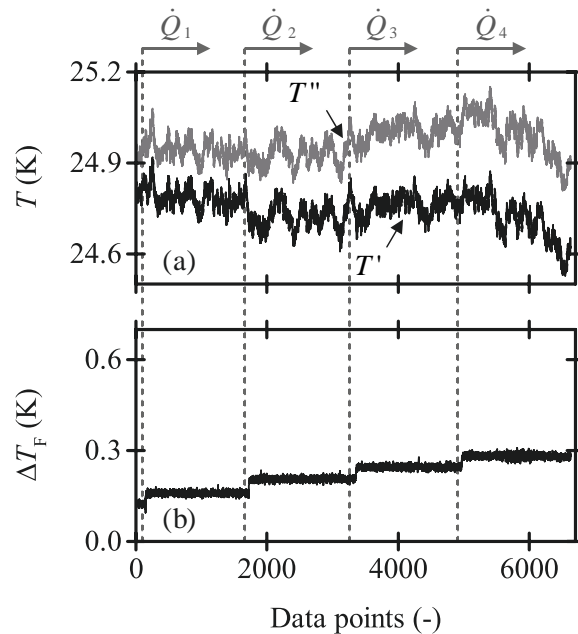
Figure 6. Inlet (T') and outlet (T'') raw temperature readings for one self-calibration run at approximately 30 K with supercritical He (a) and corresponding fluid temperature difference ΔT_F (b).

the self-calibration procedure, even for induced temperature steps far below any common cryoplant fluctuation.

For the investigation of flow rate fluctuations during the self-calibration procedure, Figure 7 shows exemplarily the Venturi tube readings at about 70 K again with supercritical He. During this run, the Venturi tube recorded a max-min fluctuation of 0.33 g/s, which corresponds to a relative fluctuation of 5.7 %. The self-calibration procedure must be sensitive to fluctuations, as it would otherwise fail its purpose (of sensing the flow rate). Flow fluctuations change the thermal resistance R, resulting in an increased measurement uncertainty. For this particular measuring point, a flow rate of $\dot{m}_{\text{Prototype}} = (6.09 \pm 0.5)\,\text{g/s}$ ($k = 2$) is calculated from the self-calibration procedure, yielding a relative measurement uncertainty of 8.1 %. Taking into account that this value results from *all* statistical fluctuations, the calculated uncertainty can be considered as a direct measure of the actual flow instability in the cryoplant during the calibration procedure. The obtained uncertainty can thus be used as criterion for accepting or rejecting calibration data as a reference for analogue measurements.

5. Conclusion and Outlook

This paper presents experimental results with a prototype flowmeter for cryogenic helium applications. With its ability of self-calibration, the flowmeter eliminates all systematic measurement uncertainties in the flow rate. This unique feature enables a calibration under real cryoplant operation; a comparative calibration under laboratory conditions is not required. The flowmeter features a compact design, a negligible pressure loss and a negligible required heat input for the thermal measurement. The prototype flowmeter was tested in a control cryostat of the TOSKA facility at KIT. An existing Venturi tube, installed in series with the prototype was used for reference measurements. The experiments were conducted with gaseous and supercritical helium from a 2 kW helium refrigerator at approximately 30, 50 and 70 K.
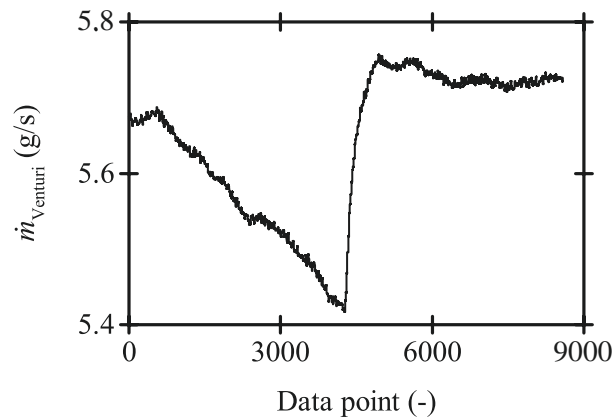
Figure 7. Venturi tube readings for a self-calibration run at approximately 70 K with supercritical He.

The experimental investigations reveal very good agreement of the measured mass flow rates within the measurement uncertainties. The shown results proof the self-calibration ability under real cryogenic operating conditions, implying cryoplant-dependent temperature and flow rate fluctuations. Hence, the results were used to discuss the influence of these fluctuations on the self-calibration procedure. The experiments confirm that temperature fluctuations have no influence on the self-calibration, even if they exceed the heat load induced temperature increase. Flow rate fluctuations, on the other hand necessarily influence the uncertainty of the determined flow rate. The self-calibration result provides a direct measure of the cryoplant's flow stability.

Based on the gained knowledge and experience with the prototype flowmeter, a pilot series of cryogenic flowmeters with a first version of a fully automated electronics was built for field tests at CERN, Switzerland and GSI, Germany.

The field test applications aim to expand the test range of the cryogenic flowmeter, especially to lower temperatures. First comparative measurements to a cryogenic Coriolis flowmeter at GSI proof that the new principle works also with subcooled liquid helium. The experimental data will be used to further improve the automation of the self-calibration procedure. Based on the self-calibration points, a transient measurement mode will be incorporated, allowing a continuous flow measurement with an analogue output signal.

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