



*Large Hadron Collider Project*

**LHC Project Report 1072**

**LEAK-TIGHT WELDING EXPERIENCE FROM THE INDUSTRIAL ASSEMBLY  
OF THE LHC CRYOSTATS AT CERN**

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**Abstract**

The assembly of the approximately 1700 LHC main ring cryostats at CERN involved extensive welding of cryogenic lines and vacuum vessels. More than 6 km of welding requiring leak tightness to a rate better than  $1.10^{-9}$  mbar.l.s<sup>-1</sup> on stainless steel and aluminium piping and envelopes was made, essentially by manual welding but also making use of orbital welding machines. In order to fulfil the safety regulations related to pressure vessels and to comply with the leak-tightness requirements of the vacuum systems of the machine, welds were executed according to high qualification standards and following a severe quality assurance plan. Leak detection by He mass spectrometry was extensively used. Neon leak detection was used successfully to locate leaks in the presence of helium backgrounds.

This paper presents the quality assurance strategy adopted for welds and leak detection. It presents the statistics of non-conformities on welds and leaks detected throughout the entire production and the advances in the use of alternative leak detection methods in an industrial environment.

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Presented at the 2007 Cryogenic Engineering Conference and International Cryogenic Materials Conference  
CEC-ICMC2007

16-20 July 2007, Chattanooga, USA

CERN  
CH - 1211 Geneva 23  
Switzerland

Geneva, 10 December 2007

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### **ABSTRACT**

The assembly of the approximately 1700 LHC main ring cryostats at CERN involved extensive welding of cryogenic lines and vacuum vessels. More than 6 km of welding requiring leak tightness to a rate better than  $1 \cdot 10^{-9}$  mbar.l.s<sup>-1</sup> on stainless steel and aluminium piping and envelopes was made, essentially by manual welding but also making use of orbital welding machines. In order to fulfil the safety regulations related to pressure vessels and to comply with the leak-tightness requirements of the vacuum systems of the machine, welds were executed according to high qualification standards and following a severe quality assurance plan. Leak detection by He mass spectrometry was extensively used. Neon leak detection was used successfully to locate leaks in the presence of helium backgrounds.

This paper presents the quality assurance strategy adopted for welds and leak detection. It presents the statistics of non-conformities on welds and leaks detected throughout the entire production and the advances in the use of alternative leak detection methods in an industrial environment.

**KEYWORDS:** cryogenics, LHC.

**PACS:** 07.20.Mc.



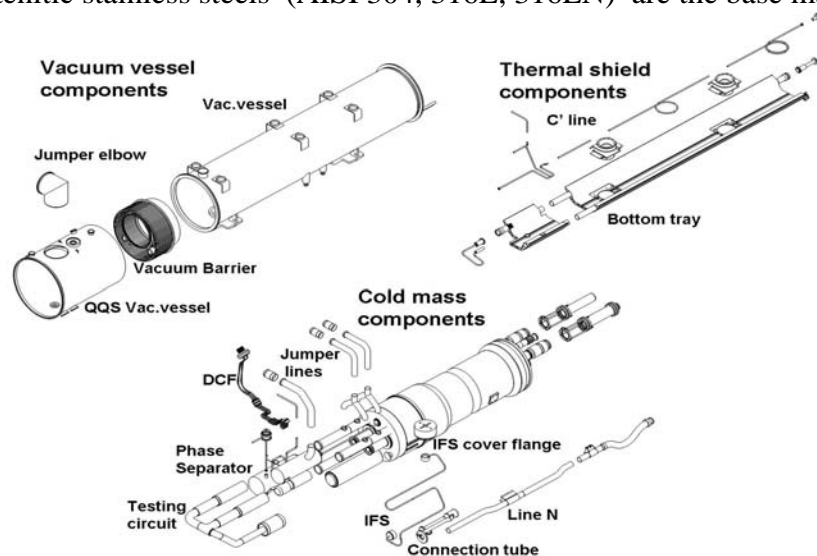
**FIGURE 1.** Pictures of the assembly halls of the LHC Short Straight Sections (left), dipole cryostats (right) at CERN.

## INTRODUCTION

The 1232 superconducting dipoles and 474 lattice quadrupoles of the Large Hadron Collider, were assembled into their cryostats in an industrial-like production at CERN (FIGURE 1). The magnets enclosed in their so-called cold masses were manufactured in European industry, whereas the assembly of the cryostat, with components also ordered in industry by CERN, was executed in the frame of a *result-oriented* contract with a consortium of firms, based on a *build-to-print* specification [1]. CERN set-up and managed the Quality Assurance (QA) plan and engaged 2 external firms for welds inspection and for the execution of vacuum and leak detection tests.

The largest work effort came from the assembly of the quadrupoles in their cryostats to form a so-called Short Straight Section (SSS), due to the complexity of these assemblies, involving a large amount of welding on a wide variety of components, resulting in 55 variants. More emphasis is given to these units in the following.

FIGURE 2 illustrates, in an exploded view, the components requiring leak-tight welding to assemble one type of SSS. Typically, an SSS requires about 50 manual and 7 automatic orbital leak-tight welds. All welds are TIG, with or without filler material. Welds cover material thicknesses between 1 and 5 mm and have lengths between 10 mm and 1 m. Austenitic stainless steels (AISI 304, 316L, 316LN) are the base materials, with



**FIGURE 2.** Exploded view of components of an SSS requiring leak-tight welding.

the exception of one butt weld made on aluminum 6060 pipes. Most welds were to be leak checked before proceeding further in the assembly which would then make them inaccessible for repair. In average an SSS requires 7 leak tests.

The SSS cryostat assembly work spanned over a period of 5 years, between 2003 and 2007, and involved an assembly team with about 6 qualified welders in average, and a QA team including 1 weld inspector and 5 vacuum leak detection technicians.

## **QUALITY ASSURANCE PLAN**

The Quality Assurance plan was set-up to comply with safety regulations for the construction of pressure vessels, as defined by CERN's Safety Commission (SC), and to fulfill vacuum and cryogenic requirements for the operation of the LHC machine.

### **Quality of Welds**

The design of the welds and their execution was first qualified internally by CERN on samples, according to European standards (EN 288-3). Test campaigns on the most difficult welds were made, in order to develop specific equipment to obtain a good inert-gas protection, and to validate cooling devices when temperature-sensitive materials (electrical insulation of bus bars and plastic fillers and spacers) were close to welds. The qualifications of welds were then repeated by the contractor through an external accredited French organization (APAVE). All welders were also certified, by the same organization, according to a European standard (EN 287-1).

A weld inspection plan was elaborated in agreement with the SC, classifying the welds on the basis of their criticality in terms of stress level, difficulty in their execution, and personnel exposure during pressure tests. Welds can be classified in two main categories: welds of pressurized cryogenic circuits, and welds on vacuum-tight envelopes at room temperature, the former being the most demanding in terms of quality.

The general acceptance criteria according to ISO 5817 class B are adopted for the welds on cryogenic circuits in stainless steel and according to ISO 10042 class B for aluminum welds. All welds had to pass an external visual inspection; some of those on pressurized cryogenic lines, where backing gas protection was more difficult to achieve, had to pass internal visual inspection by endoscope and x ray inspections. Provisions were made, in the inspection plan, to reduce the rate of checks in the case where statistical confidence would justify it. Inspections were made by personnel from an external firm, accredited according to a European standard (EN 473, level 2).

### **Leak Detection Plan**

As cold masses and cryostat components had been previously tested and certified in Industry to be leak tight, leak checks were limited to the welds made during the cryostat assembly, followed by a final leak detection test to certify the leak tightness of the finished cryo-magnet. TABLE 1 summarizes the acceptable leak requirements at the given test pressures for the cryogenic and vacuum circuits tested on an SSS.

Hold points for the purpose of leak testing during assembly were introduced whenever the welds to be checked would become inaccessible for repair due to subsequently added equipment. This strategy would also permit rapid localization of leaks and immediate repair actions if needed. Three leak detection methods, all based on helium mass spectrometry, were employed, depending on sensitivity requirements, compatibility with the circuit to be tested and the impact of the test duration on the assembly schedule.

**TABLE 1.** Leak detection (at room temperature) requirements during cryostat assembly

Envelopes	Leak-tightness [mbar.l.s <sup>-1</sup> ]	Test Pressure $\Delta p$ [bar]	Leak type in machine operation
Cold mass to vacuum vessel	$<1.10^{-9}$	25	He II to insulation vacuum
Heat exchanger to vacuum vessel	$<1.10^{-9}$	5	He II to insulation vacuum
Vacuum vessel to atmosphere	$<1.10^{-6}$	1	Atm. to insulation vacuum
Insulation vacuum barrier	$<1.10^{-7}$	1	Ins. vacuum to ins. vacuum
C', KD cryo lines to vacuum vessel	$<1.10^{-9}$	25	He to insulation vacuum
Thermal shield cooling line to vacuum	$<1.10^{-9}$	27.5	He to insulation vacuum

The most widely employed leak check of welds on pipes was the *clam-shell test*, a method developed by CERN [2]. It consists in fitting a hood, in rubber or silicone and specially made for the weld geometry, around the weld, pumping vacuum between the hood and the weld, pressurizing the tube with helium from inside, and measuring the helium signal in the clam shell vacuum.

This method is particularly advantageous when testing pipes welded to envelopes contaminated with helium, as in the case of cold masses, which had been previously helium leak tested in industry. Testing down to very low sensitivities ( $10^{-10}$  mbar.l.s<sup>-1</sup>) can be done rapidly and by a single operator. The only limitation on the method is that the hoods cannot be made for welds on complex geometries. In the SSS assembly a set of 10 different clam-shells were developed and extensively used for checks at intermediate assembly stages and localisation of leaks.

The remaining welds on helium contaminated envelopes, for which clam shells could not be made, had to be tested by *helium accumulation*. This is a commonly used method, consisting in enclosing in polyethylene pockets the welds to be tested, pressurising the circuits with helium, and measuring, after a convenient accumulation time, any change of helium concentration in the pocket by means of a helium detector sniffer. The limitation of this method, in an industrial-like mass production, is the long work interruption due to the rather long accumulation time; a way of reducing this time is to increase the pressure, but this is then limited by safety regulations concerning personnel working in the vicinity. For the assembly of the SSS, accumulation tests were carried out in most of the work places. Pressures up to 8 bar were agreed with the safety commission, needing an accumulation time of more than 8 hours to reach a sensitivity of at least  $10^{-9}$  mbar.l.s<sup>-1</sup>. Assembly work was organised so as to make accumulation tests overnight.

A final *global leak test* was made at the end of every assembly to certify its leak tightness with sensitivity better than  $10^{-9}$  mbar.l.s<sup>-1</sup>. The vacuum vessel was pumped down to  $10^{-3}$  mbar, and a global leak rate measurement was made under a pressure of 25 bar in the cold mass circuits. For safety reasons, a closed pressure test area was set-up in the assembly hall, allowing the testing, during normal working hours, of up to two cryo-magnets at the same time, to keep up with production needs.

TABLE 2 presents the number of checks and their overall duration compared to the total assembly time, for the three main SSS types (in increasing complexity from A to C).

**TABLE 2.** Leak detection during SSS assembly.

SSS type	No. of leak checks	Integrated test duration (working days)	Nominal assembly duration (working days)
Type A	4	2	10
Type B	8	3	15
Type C	9	4	20

## WELDING AND LEAK DETECTION EXPERIENCE ON THE SSS

About 20000 welds, for a total length of more than 6000 m, were executed and inspected. About 2000 x-ray shots were taken (both on witness coupons and *in-situ*). FIGURE 3 (top) summarizes the quantity of weld defects detected, classified in three main groups depending on the degree of severity and repair actions taken: I - defects within the tolerance of the norm, no repair; II - defects exceeding the tolerance, repair by local re-welding; III – defects exceeding the tolerance, repair by cutting and re-welding. The main defects encountered were, in decreasing numerical order: lack of penetration, lack of fusion, metallic inclusions, and root porosity. The plot of defects vs. production rates shows that the defects rate on welds remains below 6 %. Several learning curves can be identified, corresponding to the periods when a significant turnover of welders occurred or when a steep increase in production rates took place. The high rate of defects at the end of production corresponds to the assembly of special SSS units with very specific weld types.

3300 leak detection tests and 1100 additional working hours were executed over the whole cryostat assembly, against 2400 tests initially planned. Ninety-one leaks were detected. Only 44 % were imputable to assembly welds, with an approximately equal share over 6 welds well known for being difficult to execute. One third of these leaks were found on components, either in their welds or in the base material, which had nevertheless been delivered with leak-tight certifications from industry. Most of these leaks appeared during the global leak test at the end of assembly, and their localization and repair was lengthy and cumbersome, often requiring partial dismounting of the cryostats. The frequency of these cases justified introducing systematic incoming leak detection on certain components, explaining the additional leak detection work load. On the *connection tubes*, 3 leaks came from inclusions in the flanges made out of a faulty heat of raw material, which opened up under weld-induced stresses. Similarly, on the *jumper elbows*, leaks appeared through cracks induced by welds made during assembly. 11 % of leaks came from bad mounting of testing equipment (pinched o-rings, damaged Conflat® flanges, re-use of copper gaskets, etc.) mostly appearing during high pressure tests. 11 % of leaks could neither be localized nor explained and eventually disappeared; a possible explanation is that these were spurious signals coming from a sudden release of trapped helium. 3 SSS developed leaks appearing at cold during magnetic testing, 2 on welds of the *Dipole Corrector Feed-through* (DCF), and 1 on a cold mass weld. All could be localized and repaired after warm up of the SSS. It is worth mentioning that no cold leaks, undetectable at room temperature, were ever experienced.

Since welds were systematically inspected visually and defects repaired before being leak tested, a quantitative correlation between quality of welds and leak tightness cannot be made; in a few cases, though, when welds were tested by mistake before being inspected, leaks were found and weld defects were then detected at the same locations.

Between December 2005 and March 2006, during the highest assembly rate of the SSS, a spectacular increase in the number of leaks, mostly appearing during the global leak test, was observed. Up to 18 finished SSS were blocked by small leaks (between  $10^{-7}$  and  $10^{-8}$  mbar.l.s<sup>-1</sup>) which could not be localized due to the high helium residual in the cold mass and cryostat. A concentrated effort was brought to rapidly identify the causes of this problem which seriously affected the normal progress of all subsequent activities, especially tunnel installation of the magnets. In this frame, the use of alternative leak detection and localization methods, as explained in the following, was of great help.

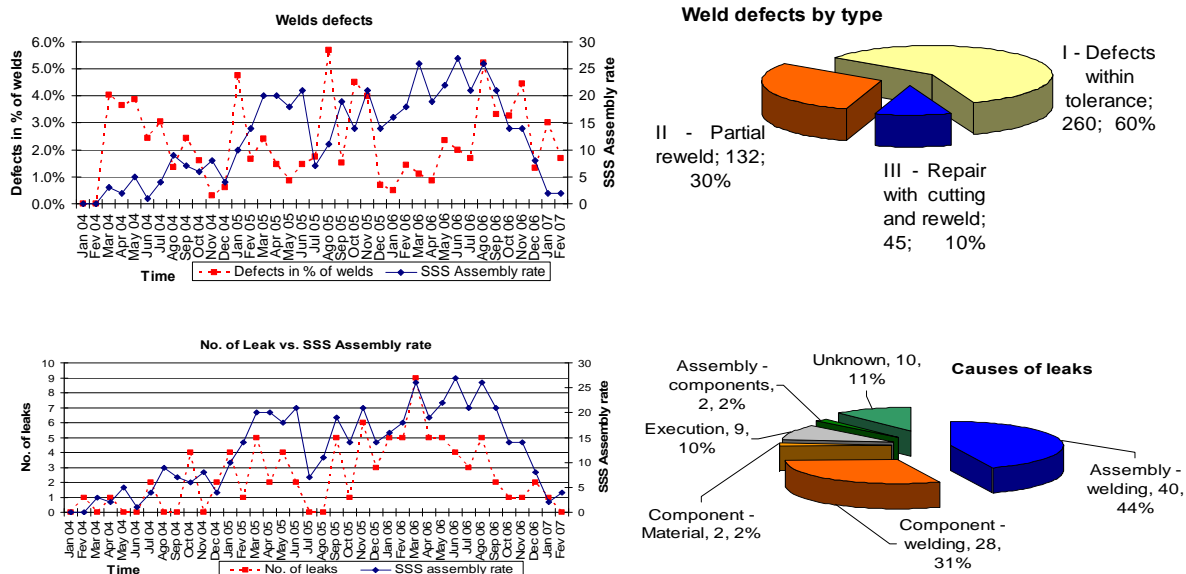


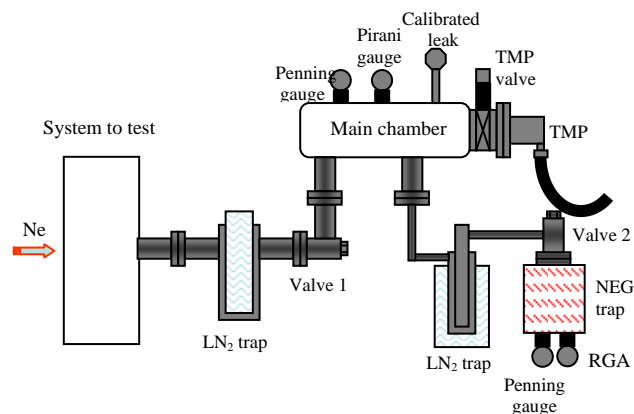
FIGURE 3. Weld defects and their share by type (top), leaks detected with their cause (bottom).

## ALTERNATIVE LEAK DETECTION METHODS

### Leak Detection Using Ne as Tracer Gas.

Leak detection using argon and neon has been extensively applied at CERN in the past. Since leak detectors for these two gases are not easily available, dedicated systems were built. Quadrupole residual gas analyzers (RGA), tuned on the relevant atomic masses of the gas in use, were employed. Since argon (amu 40) is inadequate in leak detection on welded assemblies where the same gas is used as backing protection in TIG welding, neon has to be used. But since the signal of the main isotopic mass of this gas (amu 20) is covered by that of double ionized  $^{40}\text{Ar}$  atoms, a much lower background can be obtained by detecting  $^{22}\text{Ne}$ ; its isotopic abundance remains relevant (10 % of the total neon quantity), and the signal at 22 amu is affected only by double ionization of  $\text{CO}_2$  (amu 44) which can be efficiently depleted before reaching the vacuum chamber where the gas analyzer is installed.

To profit from the gas analyzer capability, pressures in the high vacuum range must be obtained in the detection system, possibly without reducing the partial pressure of the tracer gas. On systems of the complexity of a cryo-magnet this level of vacuum cannot be reached simply by pumping at room temperature and liquid nitrogen traps are used, aimed at adsorbing water vapor, which is the main gas, and hydrocarbons. In addition, hydrogen, nitrogen and molecules containing oxygen, namely  $\text{CO}$ ,  $\text{CO}_2$  and the residual water vapor are pumped by a non-evaporable getter (NEG). The remaining gases are essentially those not chemically pumped by the NEG material, i.e. rare gases and the residual methane. The detection set-up used is illustrated schematically in FIGURE 4. It consists of a main vacuum chamber pumped by a turbo-molecular pumping station (TMP), the pumping speed of which is reduced by an orifice of known conductance. A gas analyzer equipped with a secondary electron multiplier is mounted on the chamber through a liquid nitrogen trap and a vacuum pipe (10 cm in diameter, 30 cm long) wound on the inner surface by 3 cm wide St707 NEG ribbon [3]. The tube containing the NEG, as well as the main chamber, can be isolated by all-metal valves. Total pressures are measured by Pirani and Penning gauges.



**FIGURE 4.** Schematic of Ne leak detection set-up.

To calibrate the gas analyzer, a neon-calibrated leak is installed in the main chamber or mounted on the system under test. The calibrated leak can be purchased with a neon reservoir; in this case only one value of neon flux is available. The alternative is to use a capillary of known conductance pressurized with neon at different pressures at one extremity. In this way, flux of different values can be obtained by reading the upstream pressure. The known flux produces a variation of the 22 mass peak intensity from which the proportionality factor is obtained.

Isolated by the rest of the system, the detection set-up is pumped down and, if needed, also baked-out at about 200 °C for one day. At the end of the bake-out, the NEG strip is activated at least overnight at about 350 °C [4]. The ultimate pressure after cooling at room temperature is in the  $10^{-10}$  mbar range in the main chamber, while it is beyond the Penning gauge lower limit in the gas analyzer housing. In general, after activation the gas analyzer chamber is valved-off (valve 2 closed) to preserve the NEG performance. The system to test is pumped down by an additional TMP, and when pressure is in the range of  $10^{-4}$  mbar, the liquid nitrogen traps are cooled down and valve 1 is opened. Once the pressure in the main chamber is stable, valve 2 is also opened and the mass 22 signal is recorded together with other relevant signals, namely those of masses 20 and 44. Sensitivities in the order of  $10^{-9}$  mbar.l.s $^{-1}$  can be easily obtained. The tracer gas can then be sprayed in the area under investigation.

For the sake of reducing the pump-down time on the SSS cold masses under investigation, an additional turbo-molecular pumping station was connected to its largest conductance pipe. It normally took a few days to reduce the general background in the cold mass to a level that permitted leak checking. The leak detector was then used. The TPM was throttled with a diaphragm to about 20 l/s pumping speed so as not to reduce the sensitivity of the leak detection. A neon standard leak with sensitivity of about  $5 \times 10^{-8}$  mbar.l.s $^{-1}$  was attached to the cold mass as far as possible from the detector, or, if that was not possible, between the cold mass and the TMP. Typically, the detection level for a leak, using neon 22 as the trace gas, was better than  $10^{-8}$  mbar.l.s $^{-1}$  total leak rate. Neon was sprayed around welds or into plastic pockets covering the zone under investigation. In the case of a global test, neon was injected directly inside the cryostat vacuum vessel, which was for this purpose closed by polyethylene bags on both sides.

Out of the 18 non-conforming SSS, half turned out not to have a leak, thus populating the 11 % of leaks or apparent leaks which could not be found and four were found to have leaks in the DCF. Because of the systematic occurrence of these leaks an investigation was launched, and it was found that the component was sensitive to weld-induced stress. After correction of the welding techniques, no further leaks were found in this location. Two leaks were found in temporary welded caps that were installed to seal



off cryogenic lines to permit the pressure test. Three leaks could not be localized and, considering their small size ( $\sim 5 \cdot 10^{-9}$  mbar.l.s<sup>-1</sup>), it was decided to use the SSS as such.

### Leak Detection Using SF<sub>6</sub> as Tracer Gas.

Modern halogen gas leak detectors, widely used in the high voltage switchgear industry using SF<sub>6</sub>, have excellent sensitivities in the sniffer mode ( $< 10^{-8}$  mbar.l.s<sup>-1</sup>). Normal backgrounds of halogen gas in the standard atmosphere are much lower than rare gases such as He and Ne. Considering the successful localization of a small leak by this method, undetectable using He detectors in sniffer mode, a few attempts to localize very small leaks using SF<sub>6</sub> as tracer gas were repeated in the course of the series production. The very short time allocated to use the equipment, on loan with its gas recuperation system (SF<sub>6</sub> is a greenhouse gas which must not be released in the atmosphere), and other priorities did not allow the leak detection tests to be conclusive. However it is believed that, despite the sensitivity limitation due to the larger size of SF<sub>6</sub> molecules, this technique using halogen gas leak detectors might be of interest in confined spaces with high He background and that it should be further studied.

## CONCLUSIONS

Throughout the assembly of the cryostats of the LHC magnets, defective welds remained below 6 % on monthly work, and summed up to about 2 % on the total work. Repeat learning curves appeared whenever the turnover of personnel was high or following a steep increase in work load, proving the importance of having stable and trained welders in a similar industrial-like production.

About 40 % more leak tests than originally planned were made, this increase mainly coming from additional checks on the quality of components supplied by industry, responsible for more than 30 % of the 91 leaks found, and additional tests required to localize leaks in the complexity of the assemblies. Less than half of the leaks came from assembly welding, yielding a leak-tight welding success rate of 99.5 %; most of the leaks were associated with a few types of weld, well known to be difficult to execute, and which could perhaps have been avoided by a design taking accessibility for welding into account.

Leak detection using clam-shells is by far the most convenient and practical way of making checks in an industrial production, justifying that a special care is made when designing complex cryogenic equipment to allow a generalized use of this technique.

Neon as tracer gas and a leak detection set-up using an RGA, suitably tuned on the atomic mass of <sup>22</sup>Ne, were successfully used to localize small leaks in the presence of helium background. Though this method demands expertise in UHV and in handling NEG materials, the CERN-made test set-up remains compact and quite user-friendly and should be considered as a complementary leak detection device in similar manufacturing contexts.

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