Quality Assurance during Assembly of Wendelstein 7-X

Reinhard Vilbrandt, W7-X Team

Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

To control all the work and test steps during assembly of Wendelstein 7-X for each major assembly task Quality Assurance and Assembly Plans are used as the central managing instrument. These documents ensure that the order of all steps is carried out as planned and that the envisaged quality will be met. The confirmation of a successful working step often is done by tests and measurement. For each test special instructions were prepared to ensure reproducible and correct results. The tests are either carried out by the certified QA inspectors of the project or by specially qualified internal inspectors. The most important tests and measurements are outlined briefly. All quality deviations are assessed in relation of consequences for later operation.

Keywords: Assembly Quality Inspections Assessment Magnet system Stellarator

1. Introduction

At the Max-Planck-Institut für Plasmaphysik (IPP) in Greifswald (Germany) the stellarator experiment W7-X is presently being assembled. The assembly is a very complicate process and lasts for over 9 years.

Every assembly activity has been carefully planned and qualified. Each step also must be carefully documented in order to ensure that all steps are carried out as planned and that the envisaged quality will be met. Later on all actions must be traceable to be able to find out causes in cases of faults during operation.

2. Quality assurance and assembly Plan

To control all the work and test steps for each major assembly task Quality Assurance and Assembly Plans (QAAP) are used as the central managing instrument.

They contain all essential work and test steps with the necessary input documents to be used (working instructions, drawings, welding and soldering procedure specifications, change notes, technical guidelines, collision reports, test procedures, etc.) with their document number and the right version number.

The executing organization is fixed, just like the way of interaction with the responsible parties for the component and Quality Assurance.

All output documentation like simple confirmations, measurements, test protocols, technical reports, etc. are provided if possible also with their document number.

Before execution takes place all QAAP are checked by the responsible parties, like technical responsible officers, safety, assembly organization, QM and are released by the head of the assembly division.

Unternehmung W7-X	QAAP – Assembly Cryopipes Lots 3 and 4 in MST II, part 4									2-EGG01	-Q0074.0
ASSEMBLY AND TEST SEQUENCE							FULFILLMENT				
Step No.	Description	related Documents	Completion		Information		Confirmation			Documentation	Remarks
			Type	Org.	Resp. Dept.	QA	Org.	Resp. Dept.	QA		
100	**Pipe 1-ABE10BR233**									Inspection sheet 2-NED01-Q0500.0	
100.1	Positioning of pipe **1-ABE10BR233** mark cutting site	1-ABE-T0014.0 page 35 WI 1-NEC-A0264.0	W	AS-DA Cryo				X	X		
100.6	Check Adjustment of pipe		T	AS-DA Cryo	H MC				X	Free from collisions Yes ( ) No ( )	
100.7	Protect welding area Weld Seam	WI 1-NEC-A0117.0 WPS 1-EDD09-T0834.0	W	AS-DA W				X	X	Inspection sheet 2-NED01-Q0500.0	
100.8	VT of weld seam (Videoskopie) RT if necessary	TP 1-NED-A0021.1	T	QA				X	X	2-NED01-Q0500.0 PP 2-NED01-Q0466.0	
100.9	He-Leak test	TP 1-NED-A0004.4 with shock cooling	T	AS-DA-V				X	X	PP 2-NED01-Q0501.0	
100.10	All examinations successful Inspection sheets complete		C	FBL Cryo				X	X		Released Yes ( ) No ( )
100.11	Check cleanliness of pipe Clean if necessary	WI 1-NEC-A0264.0	T W	AS-DA Cryo				X	X		
100.12	Fill Cryopipes with inert gas	HM 1-NED-B0013.0 WI 1-NEC-A0264.0	W	AS-DA Cryo				X	X		
100.13	Assembly of pipe **1-ABE10BR233** completed		D	FBL Cryo		H		X			

Fig.1 Sample sheet of a Quality Assurance and Assembly Plan for cooling pipe assembly

Reinhard.Vilbrandt@ipp.mpg.de

Each step must be signed by the responsible person and the continuation of the assembly is only allowed after the successful execution of the steps before. For critical steps hold points for final QA are included.

In addition the fulfilled QAAP contains details on the materials used during the assembly; these are usually identified with a W7-X internal material number.

Changes of the QAAP due to deviations in quality, change notes or necessary customizations of the assembly technology, are carried out in the form of supplements exclusively by the assembly planning department.

Fig.1 shows as an example a sheet from a QAAP for the assembly of cooling pipes. The input documents are on the left, the responsibilities and confirmations in the middle and the output documentation on the right.

About 1350 QAAP of about 3500 until the end of the project have been completed now or are in processing.

3. Tests and measurements–the system

The confirmation of a successful work step is often done by test and measurement. For each test special instructions were prepared to ensure, that reproducible, correct, meaningful and comparable results are obtained.

The tests are either carried out by inspectors of the QM department, who normally have level 2 certificates acc. EN 473/SNT-TC-1A for these tests, or, mainly for assembly accompanying tests, by especially qualified internal inspectors. The internal inspectors are employees of the project who are technically competent on their subject (knowledge) and are qualified for the examinations by their experiences, routine, and further education. The QM department instructs the colleagues w.r.t. the necessary quality standards and procedures. All inspectors are appointed and have a personal stamp for confirmation of test results on protocols and in QAAP.

The supervision of the test resources by means of a central database of all test equipment in the project is a task of the QM department to provide the suitability for the examination, and to control the status of the tools (next calibration date; present user; remarks on use, etc.).

4. Main tests carried out during assembly

4.1 Nondestructive tests

Visual, dye penetrations, ultrasonic and radiographic tests as the well known NDT are used for almost all weld seams. For more details see paper P3-68.

4.2 Leak tests

A special demand especially in the plasma vessel and in the cryostat is the absolute tightness of medium feeding lines or components. Therefore all components are leak tested before their assembly. Connections made during assembly must be 100 % leak tested under often difficult conditions. And wherever it is possible, the tests are carried out under conditions, which are like those of later operation. This often determines the direction of leak detection, inside or outside pressure and the temperature during leak tests. Helium is used as standard tracer gas and the leak detection level is depending on demands $1 \times 10^{-9} \ldots 1 \times 10^{-7}$ mbar l s^{-1}.

For this several leak testing procedures and equipment were developed in IPP on the basis of the standard DIN EN 1779 and a special vacuum group established in the assembly department is responsible for these tests.

Integral tests are carried out in dedicated vacuum vessels for coils, structural support elements or ports before installation. Hot leak tests at 160°C in special test chambers are used for in-vessel-components. Leak tests in LN_2-cooled thermostats are used for preassembled parts for the cryostat. Specially made mobile solid test chambers and flexible chambers made of tape sealed foils are used for leak testing of weld seams, see fig. 2.

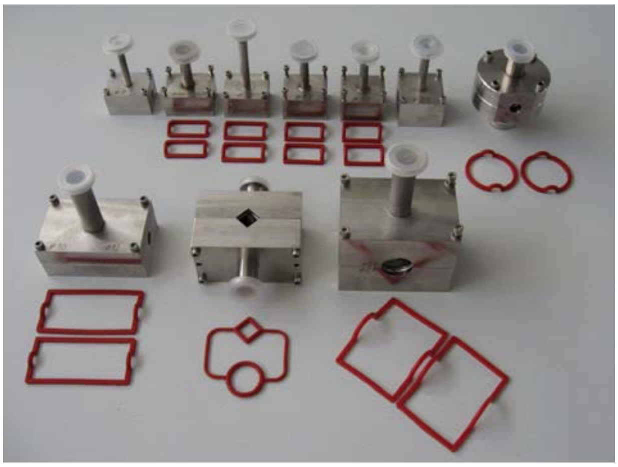

Fig.2 Set of solid test chambers for leak testing of weld seams

To simulate the stress under operating conditions the weld seams often are cooled by LN_2 or warmed up to operational temperature before or during leak tests.

4.3 Pressure tests

Gas pressure tests (for example for the bake out pipes up to 90 bars) often are carried out during assembly in combination with leak tests to save time. Water feeding components are pretested up to 50 bars after component manufacturing. And an integral test will follow after assembly.

4.4 Flow measurement

For the cooling of the cold mass inside the cryostat, supercritical Helium is used. To reduce the overall pressure drop similar components are connected in parallel to common manifolds mostly. In order to ensure an equal distribution of the flow rate amongst the components similar flow resistance must be ensured. Therefore pressure drop measurement with gaseous helium are made on all components to detect improper influences or faults e.g. in the superconductor of the coils, the bus system, the different cooling lines of coil casings and central support structure. The use of Helium instead of e.g. Nitrogen shall prevent pollution of the superconductor in coils and busses; helium will be used also in later operation. To have a consistent and reliable measurement it turned out, after some trials that the use of bellow-type gas flow meter yielded the best results.

4.5 Test of magnetic permeability

A very stringent requirement for the proper operation of a stellarator is the quality of the magnetic field. As a rule of thumb the field disturbance should be less than 10^{-4}. Therefore the relative magnetic permeability μ_r and the volumes of magnetizable material are limited strongly depending on the location. Inside W7-X, which means inside the outer vessel, all material must have a $\mu_r < 1.01$ (weld seams $\mu_r < 1.05$). To ensure this all material must have a certificate for this value and is checked by random incoming inspections with a Magnetoscope® (Försterprobe). In cases of doubt or after machining or welding, which can alter µr additional measurements also are carried out during assembly regularly. For the correct measurement of even small samples an extrapolation is necessary by means of special corrective curves, which were developed in the project itself for the gauge and the allowed limits.

4.6 Geometry checks

Many components must be measured mechanically before, during and after the assembly. Besides simple geometrical dimensions this also includes threads, fits, planeness, and roughness of areas. The precisions reach 1/100 mm depending on request. Most of the necessary thread gauges, plug gauges, micrometer calipers, depth gauges, etc. are industrial made. However, a number of templates for the preparation and orientation of components were designed exclusively for this single task. Special wedge scales for example are used to check finally necessary distances between components after assembly. Many measurements are also made with the Faro arm with a precision of 0.2 mm/m.

4.7 Adjustment control

To guarantee the necessary precision of the position of components many geometrical measurements ensure that the components follow a predefined tolerance scheme all along the assembly sequence from individual first positioning up to the final closure of the torus.

To get an exact base for all measurements during assembly, a reference net of 102 points was installed in the torus hall with an inner uncertainty of only 0.086 mm. The use of Laser-Tracker LTD500/800 and various sets of hidden point devices gives a practical accuracy better than 0.8 mm in the torus hall.

This primary reference point system was extended by a so called second-order-datum-point-system for photo-grammetry system AICON 3D Studio. A number of optical sticky targets are added to each component and provide a sufficient visibility of such points in complicate assembly situations. After fitting of both telemetry systems only an additional uncertainty of about 0.1 mm results by using the photogrammetry.

Till now all components of W7-X could be lined up in the predetermined tolerances (Fig. 3).

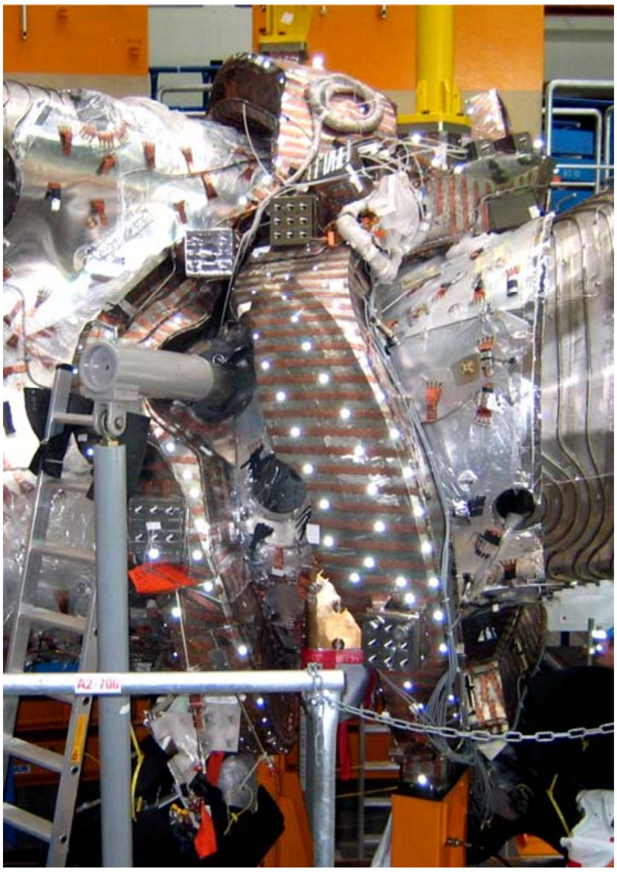

Fig.3 Photogrammetry of an adjusted coil

4.8 Collision investigations

The geometric situation of a component during assembly does not reflect the real operational situation:

- Not all components in the neighborhood are already in place and will be installed only later under somewhat more restricted conditions.
- Assembly takes place at room temperature, operation at low as 4 K.
- Due to the magnetic load all the components of the cold mass will move up to 3 cm w.r.t. the warm components.

Due to the very narrow tolerances and high require-ments on the assembly precision it was necessary that potential collisions of components had to be found out already before the assembly. Investigations were carried out with CAD models for the assembly situation at room temperature as well for cool down and several load scenarios in later operation. To increase the liability, data from 3-D laser scanning or photogrammetry of already assembled components were taken into account particularly. The results were summarized in so called collision reports. On this basis many measurements are done during the several assembly steps to check that minimal distances will be kept. These checks are carried out by simple gauges and templates but also by repeated 3-D laser scanning or photogrammetry.

4.9 Tests of the tightening of bolts

For the fastening of components like the coils to the central support structure, special bolts are used which are tightened with super-bolt-nuts. To measure the tension in the bolts an ultrasonic method is used (Bolt-Mike-device, for more details see [1]). After the final tightening of bolts the measurement is repeated three times with a time lag of 10 days each to look for settling processes. If the tension is not in the predefined limit or is not constant after this period the connection has to be redone.

4.10 Electrical tests of insulation

The insulation of the electrical conductors in W7-X (superconductor, quench detection cables) has to withstand high voltages, which can occur subsequently to quenches of the superconductors or other failures triggering a fast discharge of the magnetic system. The insulation consists in the majority of cases of glass fiber reinforced epoxy. Sometimes additional capton layers are included. All insulated parts of the electrical system are initially tested with double voltage as expected in later operation to discover defects due to manufacturing process (often manually). Retests are carried out with reduced voltage to prevent the insulation from damage (Fig. 4).

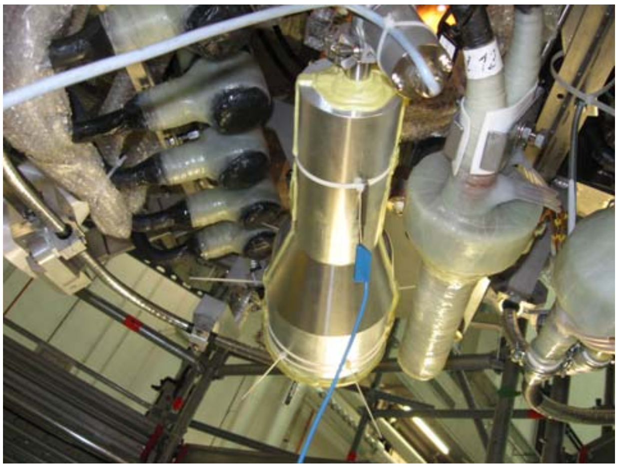

Fig.4 Local Paschentest of a superconducting joint.

A special danger during operation is the rather unlikely event to have a fast discharge together with bad vacuum conditions. This may lead to a so called “Paschen Breakdown” with a voltage of only some hundreds of volts. Therefore all conductors in the cryostat are insulated in a so called Paschen tight manner to avoid an electrical flashover in such a situation. All coils were tested before assembly with high voltages in a vacuum vessel to simulate Paschen conditions by varying the pressure as well as all busbars were tested finally after fabrication. During assembly the insulation of all connections like joints between coils and busbars, potential breakers and other parts that are often wrapped manually in a very tricky procedure are tested using portable Paschen test chambers.

4.11 Tests of sensors

Tests of all installed sensors (different kinds of temperature sensors, Rogowski- and saddle-coils, strain gauges, contact sensors, quench detection cables, etc.) are carried out after installation and subsequently after all main assembly steps. This shall confirm their functionality and gives the chance to repair sensors if necessary. In this way the risk to have sensors already damaged at the end of assembly is minimized.

4.12 Cleanliness examinations

To ensure that all surfaces and materials fulfill the demand of the (ultra) high vacuum environment many outgassing tests have been carried out to check the suitability of materials and manufacturing method before their use. In addition, each component is checked for its cleanliness before installation, either by a separate vacuum test or by other means (wiping with clean cloth, UV-lamp, etc). Because of the long assembly process and the not always optimal possibilities of protecting all surfaces these cleanliness examinations must be carried out continuously as a part of the regular assembly process to detect areas, which have to be cleaned again.

5. Final test result assessment

All quality deviations which are found during assembly are estimated in relation of consequences for later operation. This is done in the same central database which is used for risk assessment of change requests and change notes. All deviations are assigned to one or more related subsystems of W7-X like magnetic field, magnets, insulation, cooling, etc.

First a risk group is assigned to every deviation acc. to DIN EN 61511-3. This classification of risks describes an additional risk in comparison with the risks according to the reference specification. Classes reach from 0 (no risk) over 1 (negligible risk) and 2 (unwanted risk, but risk minimization is not practicable) to 4 (not tolerable risk). The risks are formed from the combination of probability of appearance and grade of consequences (table 1). After this all deviations are classified regarding their possible restrictions in later operation of W7-X (table 2).

Table 1
Risk classes acc. DIN EN 61511-3 used for W7-X.

Probability	Consequences				
	Catastrophic	Critical	Low	Negligible	No
Frequent	3	3	3	2	
Probable	3	3	2	2	
Incidental	3	2	2	2	
Low	2	2	2	1	
Improbable	2	1	1	1	
Incredible	2	1	1	1	
No					0

Table 2
Grade of restrictions during operation.

Grade of restrictions	Interpretation
0	No restrictions
1	Restricted operation, no monitoring
2	Restricted operation, monitoring necessary

All this information will be helpful in the later commissioning and operation phase of the subsystems of the machine to minimize risks or to supervise them adequately.

Acknowledgment

All work described was done in close cooperation between the departments of W7-X, the assembly staff, and the QM-department. The good collaboration between these various partner, sometimes under strong time pressure, is gratefully acknowledged.

References

[1] R. Vilbrandt, M. Schröder, H. Allemann, J.-H. Feist, Quality assurance measures during tightening of various bolts at Wendelstein 7-X, Fusion Engineering and Design 84 (2009) 1941-1946