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Contribution of IFJ PAN to the construction of the WENDELSTEIN 7-X stellarator (continuation 2010 – 2012)

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Praca wykonana w ramach projektu *755/N-7XW/2010/0, Realizacja przez IFJ PAN zadań badawczych i inżynieryjnych związanych z budową stellaratora Wendelstein 7-X. Faza 2.*

Streszczenie

Stellarator Wendelstein 7-X jest aktualnie budowany w Instytucie Maxa Plancka dla Fizyki Plazmy w miejscowości Greifswald (filia MP IPP Garching) w Niemczech. Porozumienie między MP IPP i IFJ PAN o współpracy przy budowie W7-X zostało podpisane w 2007 r. W ramach podpisanego porozumienia wraz z późniejszymi aneksami IFJ PAN zobowiązał się do wykonania następujących zadań:

1. Zainstalowanie systemu połączeń cewek nadprzewodzących we wszystkich modułach stellaratora.
2. Wzięcia udziału w zaprojektowaniu urządzeń koniecznych do manipulowania, transportu i montażu części zbiornika zewnętrznego stellaratora.
3. Wykonanie 30 kompletów części mechanicznych do polichromatorów używanych do diagnostyki plazmy.
4. Połączenie zainstalowanych systemów zasilania cewek nadprzewodzących pomiędzy modułami.

Zadanie No 2 zostało zakończone w 2008 r., zadania No 1 i 3–w 2011 r. a zadanie No 4 – w 2012 r. Ogólny zakres zadań 1, 2, 3 oraz szczegółowy opis prac wykonanych w latach 2008 – 2009 zostały przedstawione w [1], [2], [3]. Okresowe sprawozdania z prac wykonanych w latach 2010 – 2011 zamieszczone są w [4], [5].

Abstract

The Wendelstein 7-X stellarator is now being assembled at the Max Planck Institute for Plasma Physic (IPP), Greifswald, Germany (branch of MP IPP Garching). The Agreement on Cooperation between the MP IPP and the Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences in Krakow (IFJ PAN) was signed in 2007. Within that agreement IFJ PAN has taken over the following tasks:

1. to assembly of the bus bar system powering the superconducting coils of the stellarator;
2. to take a part in design of equipment for handling, transportation and assembly of outer vessel;
3. to manufacture 30 sets of mechanics for polichromators used in plasma diagnostics;
4. to connect the bus bar systems between modules (at so called Module Separation Planes).

The Task No 2 was completed in 2008, tasks No 1 and 3 – in 2011 and the Task No 4 - in 2012. General scope of the tasks 1, 2, 3 and the detail description of work done in 2008 – 2009 were presented in [1], [2], [3]. Work done in 2010 – 2011 was periodically reported in [4], [5].

1. Introduction

Stellarator Wendelstein 7-X (W7-X) being built currently in Max Planck Institute for Plasma Physics in Greifswald, Germany (IPP), is a scientific device designed for the study of very hot plasma and research of new materials for construction of next generation plasma generators. Plasma trapped in such device has so high thermodynamic parameters (pressure of few atmospheres and temperature near 100 millions deg) that such conditions are good enough for occurring fusion reaction of hydrogen heavy isotopes, which itself is a source of a very, very big amount of energy. That is a very prevalent dream to construct in some not too far future the power plants based on that idea, which are not limited by the availability of fuel, neither with a quantity of energy nor in time – some rough estimations are giving resources for next few millions years, even with ever growing demand on energy consumption. Such power plants would be also friendly for environment as their only product is an inert helium gas which by the way becomes more and more deficit strategic technological material. Nuclear fusion reactor can not explode as that process is self decaying and radioactive by-products are in much smaller quantity and less harmful than from classical nuclear plant.

The concept of W7-X design is very innovatory. Starting point is the modeling of the magnetic field which is necessary for stable plasma conditions. That is done with a help of modern numerical methods and very powerful computers. Once we have the desired distribution of field, shapes of magnetic coils are calculated with so called 'target field method'. Again a lot of computing power is necessary. There are 50 coils with complicated non-planar shapes necessary for reproducing desired magnetic field distribution. 20 additional planar coils are added to the design for expanding the range of conditions for studying stability of plasma.

Stellarator W7-X is a very massive devise, total weight is more than 750 tons, external diameter about 15 m and height 5 m. Its core is the plasma vessel in a form of strongly deformed torus, reflecting a shape of magnetic field. Around that vessel superconducting coils are placed which are producing 3 Tesla magnetic field in a center of plasma chamber. Complete design has a 5-fold symmetry so all construction is divided into 5 nearly identical modules and each module has also point inversion symmetry. As a result, 5 different types of non-planar coils and 2 types of planar coils are used in a construction. All those heavy elements are suspended on a massive central ring. Space between coils and around central chamber is tightly packed with many different elements: superconducting cables connecting coils (called bus bars) with their holders and clamps, cooling helium pipes, many different sensors, kilometers of so called instrumentation cables, also very carefully fixed to some rigid structures and so on. Additionally, there are many 'space windows' around for suspension and ports giving access from outside to the plasma vessel. As a result we have a very complicated three dimensional structure which can be designed and built only with a help of the 3D computer aid and sophisticated measuring technology. That is also rather trivial statement that quality assurance is very crucial in the project as many operations cannot be corrected after.

Task No 1

The assembly process of the bus bar systems starts on the test stand MST-II in the assembly hall, Fig.1. On that stand the pre-assembly of bus bars takes place, which includes mounting and precision alignment of bus bar positioning supports (holders, group I), installation of SA (Spulenabschluss) holders, coil current lead supports, installation of all 24 bus bars, installation and alignment of all remaining bus bar holders (group II), precise alignment and marking of relative positions between bus bar ends and coil current leads for future electrical connections (so called joints), and marking positions of clamps for bus bar bundles. Next, the bus bars are dismounted from the module and transported to the preparation area where they are prepared for final installation and connection. When the preparation of the bus bars is finished, they are installed once again on the module and cramped with the whole system of holders and clamps to compensate excessive forces acting on current conductors in the presence of magnetic field (the test stand MST-IIIa in the torus hall, Fig.1). The assembly process of the bus bar system on each module consists of the following steps:

1. Installation of bus bar holders on the central ring and coil headers;
2. Trial installation of 24 bus bars on the module including final shaping of the bus bar ends to match coil current leads;
3. Completion of 48 bus bar ends in a preparation area;
4. Final installation of 24 bus bars on the module;
5. Assembly of 28 joints (mechanical and electrical connection of the bus bar ends and the coil current leads);
6. Electrical insulation of the assembled joints;
7. Assembly of the Quench Detection (QD) system on all joints;
8. Conductive painting and clamping of 28 joints;
9. Final checking of the module, resolving possible collisions.

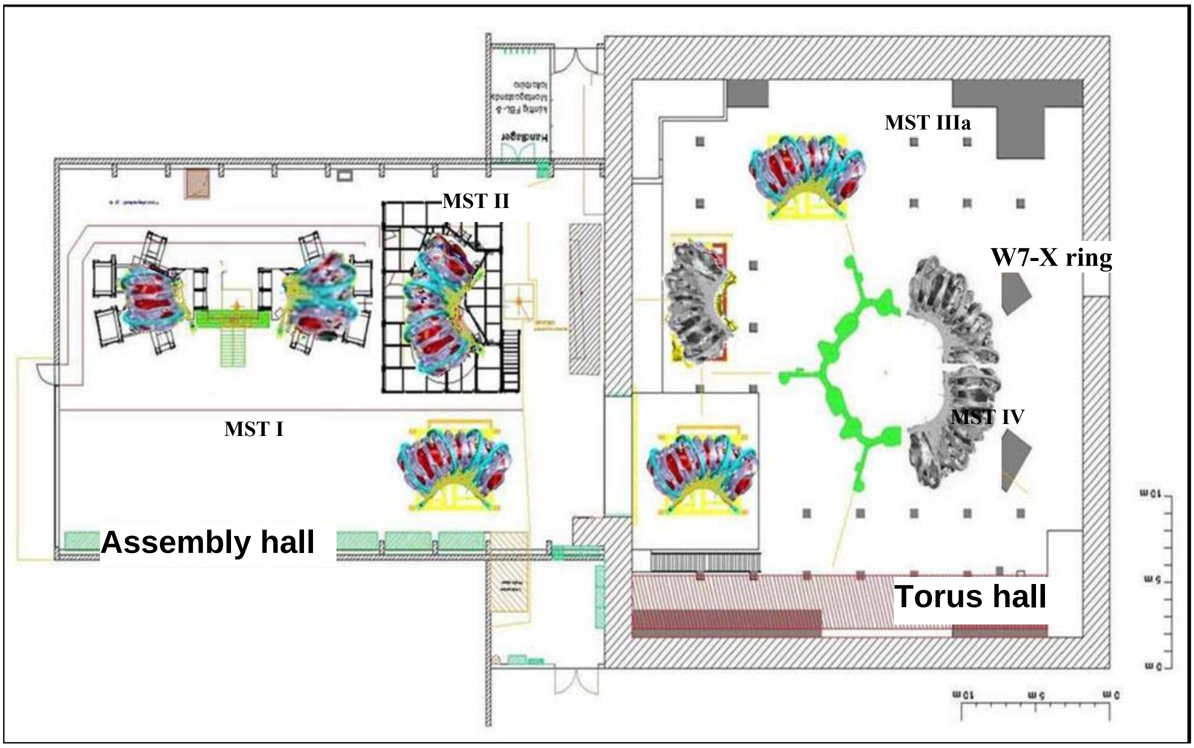

Fig.1 Arrangement of the assembly stands (MST) at IPP Greifswald

Task No 3

The IPP Diagnostic Group has been preparing itself for quality check of the plasma beam in the stellarator W7-X. Between other tools used by them for this are so called polichromators. That group asked IFJ PAN to manufacture 30 sets of the polychromator mechanics. Other necessary stuff (optics, electronics) is to be provided by IPP. The technical documentation of the mechanical components was prepared by IPP, however, IFJ PAN was also involved in its finalization and completion. Three sets of the mechanics passed successfully tests at IPP during the first quarter of 2010.Necessary modifications were included in the production process of the remaining sets. 27 manufactured sets were shipped to IPP Greifswald end of June 2011.

Task No 4

The connection process of the bus bars between neighbor modules could start when, at least, two modules are placed in their final positions, i.e. on the W7-X ring (MST IV, Fig.1). The areas of the module interconnections are called the Module Separation Planes (MSP). The following sequence of the module placements on the ring was applied: M5, M1, M4, M2, M3. Thus the first interconnection being made was MSP 5-1 and then MSP 4-5, MSP 1-2, MSP 2-3, MSP 3-4. Connection of the bus bars on each MSP has been performed in the following steps:

1. reinforcement of QD wires, if not done earlier;
2. assembly of 8 or 10 joints (mechanical and electrical connection of bus bar ends coming from neighbor modules);
3. electrical insulation of the assembled joints – part 1, then time window for helium piping and leak tests;
4. electrical insulation of the assembled joints – part 2;
5. assembly of Quench Detection system (QD) on all joints;
6. conductive painting and clamping of joints.

2. Assembly of bus bar system powering superconducting coils

Detail descriptions of each assembly steps is included in [1], [2], [3], [4] and [5]. Below short summary is presented.

1. Installation of bus bar holders on the central ring and coil headers.

It begins with installation of so called positioning holders (group I): 23 pieces on a central ring and 24 on coil headers. Those holders are defining position of bus bars within an accuracy of 1,5 mm. The position of every holder is verified with a laser tracker. The holders themselves need very often mechanical modifications, because coil headers cannot be made with a good enough accuracy. Coil terminals are fixed with so called SA holders.

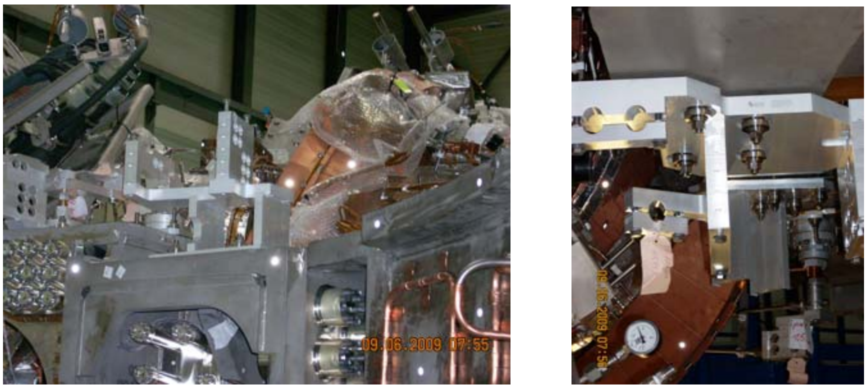

Fig2. Some holders mounted on the central ring

2. Trial installation of 24 bus bars on the module including final shaping of bus bar ends to match coil current leads

After completion of holder installation a trial assembly of the bus bars takes place on the module (Fig.3). The most important part of that task is an adjustment of the ends of bus bar to the terminals of coils for future electrical connections (joints). The adjustment requires bending of not insulated ends of the bus bars. Positions of special welding steel-Alu adapters (so called T&C adapters) are also marked with sub-millimetre accuracy. After that 33 supplementary holders of group II are installed on coil headers, positions of clamps and bus bar thermal insulation zones are marked. Then the bus bars are dismounted and transported to the preparation area.

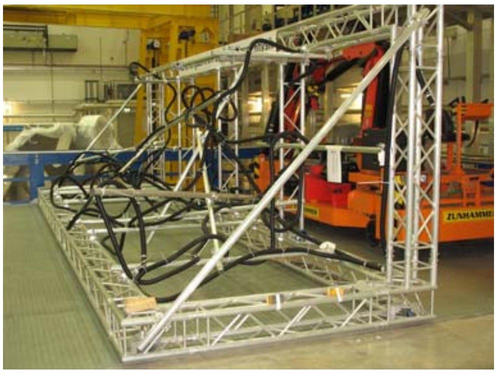

Fig3. The bus bars from Julich (left) pre-assembled by IFJ PAN team (right)

3. Completion of 48 bus bar ends in the preparation area

First, ends of the bus bars have to be dismantled from Al jacket up to marked position of T&C adapter, Each bus bar is stripped from one side then T&C adapter is welded and leak test of weld is performed at 30 bars of helium inner pressure. The whole procedure is repeated on the second end. Next superconducting wires are untwisted into 81 triplets and tinned. A careful inspection is performed to avoid any damage to the wires and to be sure the wires are covered with a tin uniformly.

Along the bus bar, under the five layers of combined kapton-glass fibre band-epoxy resin insulation, two wires in a thick kapton insulation are going for quench detection (QD). Additional two QD wires are attached on each end to the Al jacket of the bus bar (shock welding). The four QD wires are pulled out through a special glass-resin composite sleeves covering T&C adapters. Both ends of the bus bar are insulated in a similar way as the rest of the bus bar. After the curing of lamination the ends are covered with two layers of a special conducting paint.

The insulated ends are tested separately with a high voltage under the controlled vacuum in the range of Paschen effect (avalanche electrical discharge). That method of testing is very sensitive to any imperfections in insulation integrity. At the end, sleeves for clamps are glued on the bus bar in the positions marked during pre-assembly. The bus bar surface between sleeves is wrapped with a perforated self adhesive Al foil as a reflector for a thermal radiation, Fig.4.

Fig4. Bus bars ready for the final installation

4. Final installation of 24 bus bars on the module

During final installation of the bus bars on each module (Fig.5) there is necessity to complete their supporting system i.e. to fix holders and screws by tack welding, to enforce some SA holders with additional welded ribs, etc.. Very important part of the finishing work is handling with so called Red Cards. That is a part of quality management procedures. All Red Cards must be closed (problems/and conflicts resolved) before transportation of the module to the final position on the W7-X ring. An example of the procedure applied is correction of SA holder position after scanning in situ and analysis of the 3-D computer model.

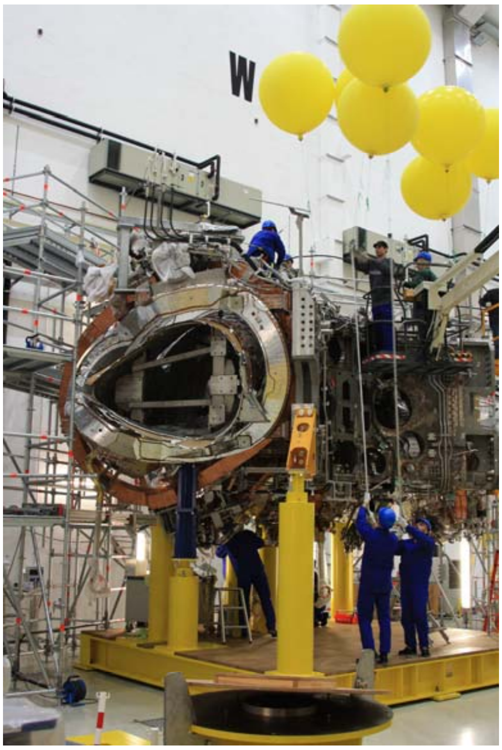

Fig.5 Final assembly of the bus bars on Module 5 with use of helium balloons

5. Assembly of joints (mechanical and electrical connection of bus bar ends and coil current leads)

The whole process of joints assembly is supervised by IFJ PAN management team. The assembly process requires interaction of the IFJ PAN technicians and other departments of the IPP. Coordination of different operations is very important for such a complex process in order to keep the time schedule under control. For example, during mechanical assembly of the joints a welding takes place twice, followed with checking both, the weld quality and leak-tightness. Welding, quality inspection, leak-testing and scanning of the joint position are done by other IPP groups.

Assembly of the joint starts with an alignment of bus bar and coil terminal to the joint body and welding lips of both T&C adapters. After leak test superconductor triplets are fixed in the body through the Al cone. Then triplets from both sides are arranged in interlaced and crossed layers and soldered in pairs one by one (Fig.6). Pre-arrangement of triplets must be done in a such way that whole bundle of soldered pairs forms near cylindrical shape, which then is cramped mechanically in a clamp. The join is then closed with the end cap. There is only 0,05 mm of clearance between the join clamp and the inner cylinder of the end cap, so one can imagine that all assembly process must be done with the highest precision. End cap and body are welded together and again leak tested.

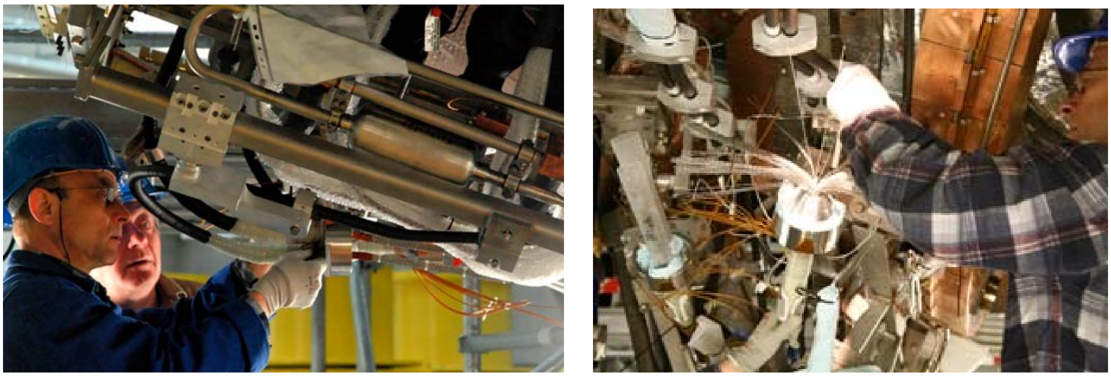

Fig.6 Mechanical (left) and electrical (right) connections of joints

6. Electrical insulation of the assembled joints

After mechanical assembly electrical insulation starts. The insulation process is time consuming and requires great care. Strict follow up of the work instruction is necessary. One has to remember that if the insulation fails during high voltage test (5 kV Paschen test) redoing or repair will anyway affect the final quality of the W7-X stellarator. On the other hand the process is rather well known and it is called “wet wrapping”. Whole joint is wrapped with many, at least eight, layers of glass fibre tapes soaked in epoxy resin. The insulation process is split into three steps during 3 days to ensure proper curing of the epoxy and to avoid a deformation of too thick and too heavy insulation.

Fig.7 Electrical insulation of joints

7. Assembly of Quench Detection system (QD)

Six teams two persons each, Polish and German, of highly skilled technicians performed this work in two shifts. First, measurements of continuity between QD wires in different configurations are required. If there is no fault the QD wires are labeled, correctly set, cut, soldered, and electrically tested once more for eliminating any mistake. Finally, the soldered wires are cast in the QD boxes with special StyCast resin. The QD wires configuration is checked again after casting QD boxes and then Paschen test of the entire joint is performed.

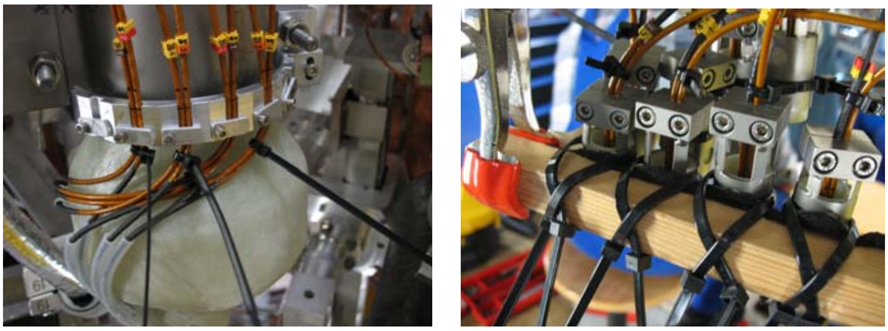

Fig.8 QD wires tested and correctly set (left), ready for casting (right).

8. Painting and clamping of 28 joints

Finally all joints together with the QD systems are painted using a special, conducting paint which forms an electrical screen around joints, so called "Faraday cage". Then, the joints are fastened to the stellarator structure in precisely determined locations (casted within their shells with a mixture of epoxy and short glass fibres).

Fig.9 Two joints with QD boxes already painted and fixed

9. Final checking of the modules

The last action before official finishing of work concerning bus-bars and joints of any module is so called "conflicts check" i.e. verification whether positions of the mounted bus bars are within desired tolerances. This was done by scanning of the bus-bars, their holders and assembled joints with the help of 3D scanner by survey teams. The scanning data are delivered to the Design Office, where "as-built" positions are compared to "as-designed" ones (Fig.10). Eventual conflicts (too small distances) are identified and correction measures are decided. For every module few such conflicts were identified. Most of them, after detailed analysis, were decided as "use as is" and for some of them necessary corrections were made.

Ergebnisse	Konfiguration→	RT	4K	HI	LI	LS	ST

(in mm)	↓Wert						
	as-designed-Geometr e	39.9	46.2	42.7	46.4	44.8	43.9
	as-built-Geometrie	37.1	43.4	39.9	43.6	42	41.1
	Wert im as-designed-WCS	-3.9	2.4	-1.1	2.6	1	0.1

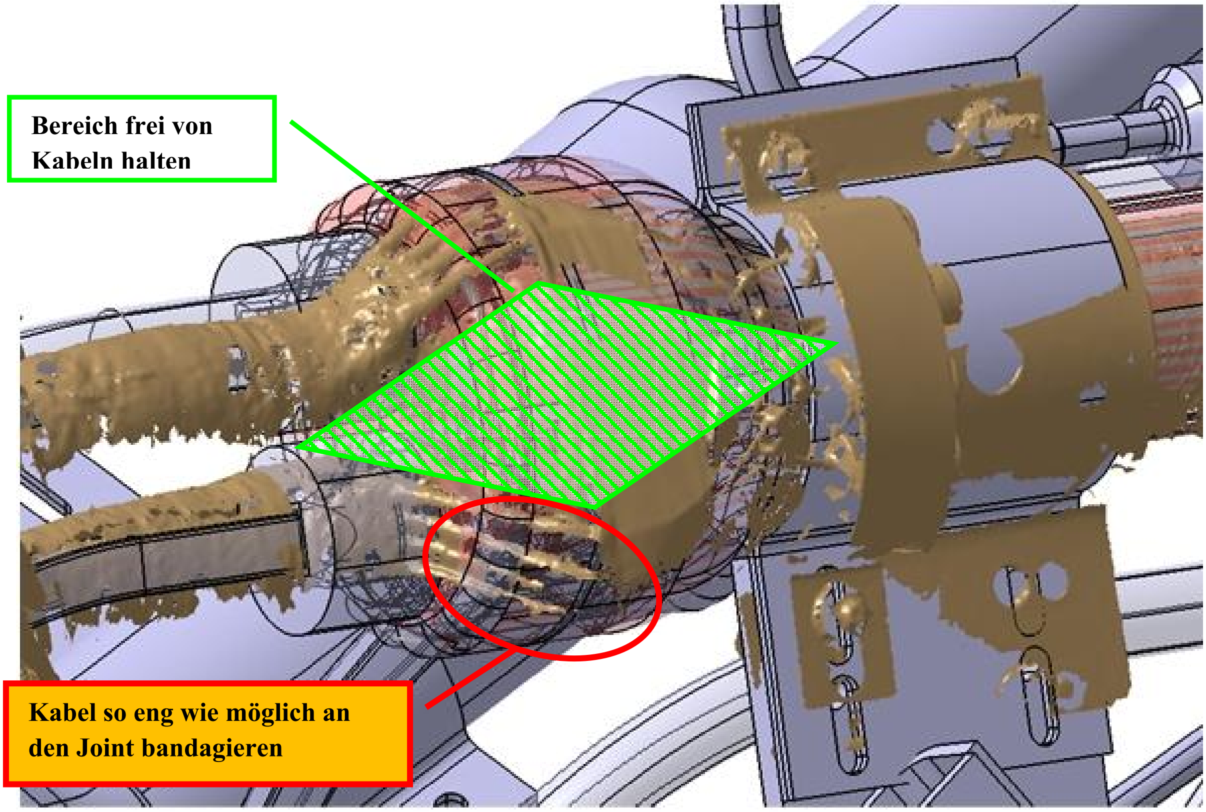

Fig.10 An excerpt from "conflicts report" drawn up by Design Office; brown scan shapes are superimposed on the 'as design' in gray colour.

3. Line Officers (LO)

The scope of work in 2010 - 2012 was realized by roughly 40 technicians (30 from IFJ PAN and 10 from IPP Greifswald) conducted and supervised by 3 Line Officers (LO) from IFJ PAN. The Bus Bar Assembly Team consisted, on average (at a given time) of 15 technicians and 3 Line Officers (LO) working on W7-X construction in two shifts. Some redundant persons were skilled as a rotation reserve, both the LO and technicians. The Line Officers from IFJ PAN were responsible for:

- work organization of the Bus Bar Assembly (BBA) team within the schedule of W7-X Construction Project;
- coordination of works with welding division, vacuum group and electrical test group also involved in assembly of the bus bar system;
- solution of technical problems encountered during the assembly process;
- modification of work procedures and instructions according to new solutions;

- instruction and training of supervised technicians;
- supervision and quality assurance of work performed by the technicians;
- completion of work documentation.

Some results of the IFJ PAN Line Officer work are listed below:

a) Training of technicians:

- assembly of joints – 10 persons,
- electrical insulation of joints – 16,
- assembly of QD system – 10,
- electrical insulation of joints at MSP – 10,
- assembly of QD system at MSP – 6.

b) Technical problems encountered:

- problems with accuracy of coil headers and alignment of bus bar holders – supplementary scan analysis was proposed and assembly process was modified, also many online modifications to the holder fixing were done;
- damaged wires during bus bar dismantling (discovered within a training period) – new tools designed, work instruction modified, all proved and applied, problem completely eliminated;
- difficulties in joint assembly – application of new solutions and tooling practically eliminated the problem, only very few cases after;
- reparation of damaged QD wires – contribution to validation process speeded up getting the final method.

c) Modification of work procedures and instructions:

- dismantling of bus bars;
- insulation of bus bar ends,
- enforcement of QD wires, operation added to bus bar preparation, join assembly on modules (coil side) and MSP,
- assembly of joints,
- electrical insulation of joints in modules,
- electrical insulation of joints at MSP.

4. Manufacturing of mechanics for polichromators

Tests of the prototype mechanics performed by IPP Greifswald showed that small modifications of specific components were necessary. IPP Greifswald prepared the final drawings in collaboration with IFJ PAN. During 2010 – 2011 the whole mechanics was manufactured. Three sets were assembled at IFJ PAN before shipment to IPP Greifswald. Parts for those 3 units were randomly chosen. Pre-assembly of the three units confirmed correctness of the manufactured components.

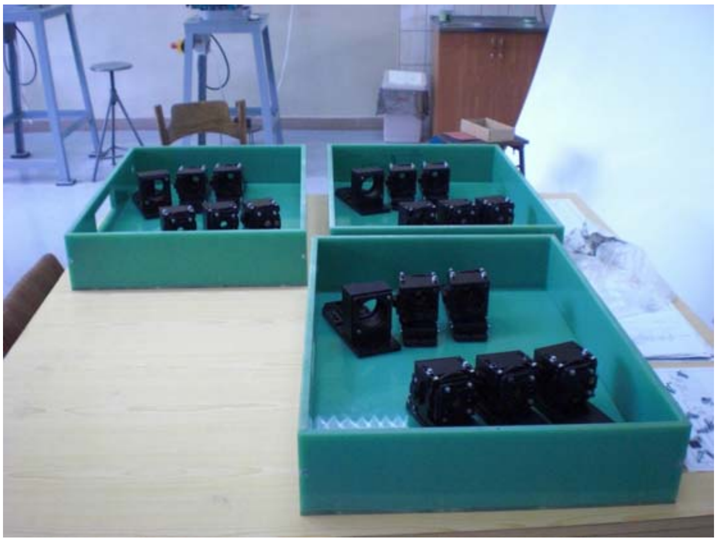

Fig.11 Three sets assembled at IFJ PAN

5. Connection of the bus bar systems between neighbouring modules

In August 2010 preparation for electrical connections between modules at the Module Separation Planes (MSP) has started. The joints at the MSPs are similar to the joints within modules themselves, however, they are made in different conditions. In addition, the MSP joints need extra adapters for precise positioning of the bus bars coming from neighbouring modules. That is the reason why new work instructions have to be written and the whole process to be qualified. Three models of the joints were prepared according to the proposed procedure, their insulation tested under vacuum (Paschen test) and then sent for the test of the resistance in the temperature of liquid helium and cryogenic cycling, then insulation was tested once again. Required resistance in superconducting state has to be lower than 6 nano-ohms, tests gave results about 100 times smaller.

Reinforcement of the QD wires (1)

At the beginning of the project some extra reinforcement of QD wires was not foreseen at all, but when we started joint assembly on module 5 we discovered few places where multilayer kapton insulation of QD wire was cut on the sharp edge of glass/epoxy composite just on exit of the wires from bus bar insulation. The same problem on the coil side was observed too. From that time all QD wires were reinforced by PE tubes and additional wrapping. Of course this new operations, both insulation repair and enforcement, have to be qualified, so several samples were prepared and tested according to quality assurance procedures. That reinforcement was added to the bus bar preparation but starting from the module 4 when the bus bars for module 5 and 1 were already finished (modules were assembled in the order 5-1-4-2-3,). In completion of modules 5 and 1 reinforcement was done just before joint assembly, but excluding those bus bar ends which go to the interconnections – it was decided to include that work to the assembly of interconnections themselves. In the case of MSP 5-1 bus bars coming from both sides needed that kind of protection. That work was completed in May 2011. In MSP 5-4 and MSP 1-5 reinforcement had to be completed only from one side.

Assembly and insulation of the joints (2, 3, 4)

Assembly of joints in interconnections was very similar to the assembly on the modules. There was necessity to add two extra adapters, one for vertical compensation (extra space was foreseen in design for the offset between modules, so always bus bar ends from one of the modules were ‘shorter’); second, so called eccentric, for compensation of the horizontal distance between bus bars.

After alignment of all parts, the T&C adapters on bus bars were welded with the compensating elements and joint bodies and then leak tests were performed. 81 triplets from each side were arranged in 9 layers in such a way that every triplet from one bus bar meets its counter partner from the other side. Those pairs are carefully soldered together and at the end whole bundle of pairs is formed in a nearly circular cross section. All joints in interconnections are nearly vertical, so soldering operation is also more difficult, because melted tin has a tendency to flow down and extra attention has to be paid. After that joints are clamped very tightly, screwed and welded with a joint end cap, and then again leak tested. Preparation of joints for connection in MSP 5-1 was done in June 2011, electrical connection and closing was finished in July 2011.

When mechanical assembly is completed electrical insulation of joints can start. Generally, insulation of joint is a multilayer wrapping with a glass tape saturated with epoxy resin. Wrapping has to be very tight, with no voids or dry regions. After curing it should be very uniform, solid-like composite. As total thickness of insulation must not be less than 5 mm that cannot be done in one run, because that is too heavy and would be deformed during curing time to the unacceptable degree. Main operation is divided into three steps separated with a curing time, in practice to the next day. Together with other steps it takes 10 days, but of course can be optimized if there is more than one joint to do. In the case of MSP joints all but one are with a helium outlet – insulation process has to be divided into two steps interrupted by installation of helium piping.

Fig.12 First step of insulation process (left); second step (right).

First, only the lower part of the joint is insulated. Then the connection to the cryogenic system is done by welding helium supply pipes together with so called potential breaker – coils, bus bars and joints are also part of helium circulation, but electrically isolated from cryogenic supply. After all necessary leak tests of many welds, an electrical insulation is continued (part II). At that time not only rest of joint body is wrapped with glass-epoxy but also part of the helium pipes up to the middle of potential breaker.

Assembly of Quench Detection (QD) system, painting and fixing of the joints (5, 6)

Next task is assembly of joints QD (Quench Detection) system. A sophisticated electrical scheme consists of 8 QD wires exiting from each joint connected to external, so called instrumentation cables, and casted with special resin (StyCast) in small, fibre glass cylinders called QD boxes. During whole procedure 3 electrical tests are performed, verifying each time the correctness of electrical connections and configuration. After completion of QD wiring the joint together with QD boxes is closed in a vacuum chamber for Paschen test, then joint insulation, ends of bus bars, QD wires and boxes are covered with two layers of conductive paint. At the end QD boxes are fixed to the joint with specially formed steel clamps, positions of all MSP elements are verified with scanning and joints themselves are casted in their shells with mixture of epoxy and glass fibres. All screw fastenings are tighten with a proper torque and secured with a tack welding.

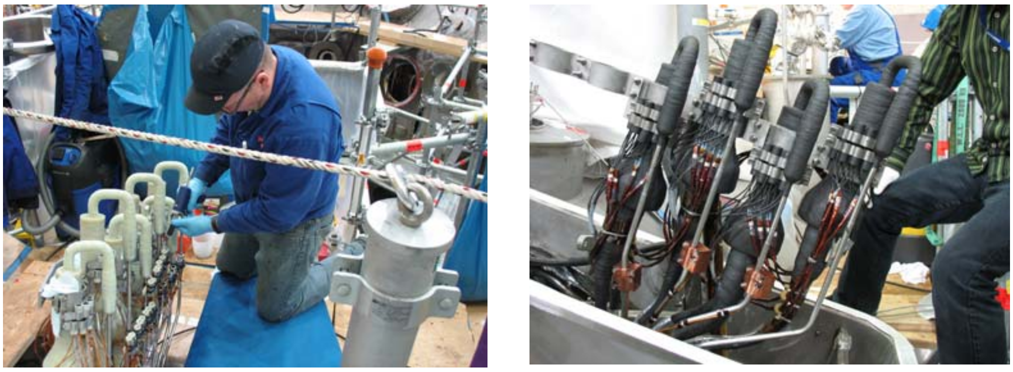

Fig.13 Casting of QD boxes (left); finished QD system of non planar coils (right)

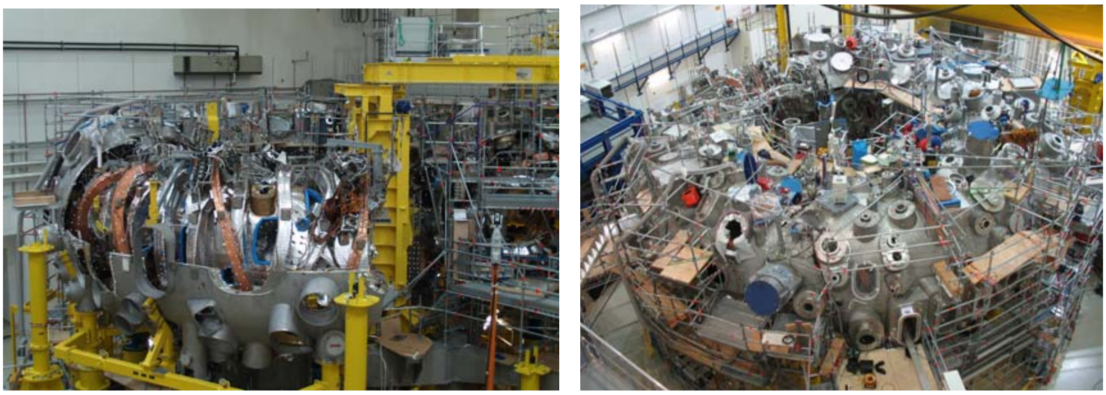

Fig.14 December 2010 - three modules placed at the W7-X ring (left); December 2011 five modules in place (right)

6. Conclusions

1. The following tasks were done in 2010 - 2012 within the range of collaboration between Max-Planck-Institute IPP Garching (IPP branch Greifswald) and IFJ PAN Krakow:
   - **Task No 1** - Completion of the bus bar assembly work packages on four modules 1, 4, 2, 3,
   - **Task No 3** – Completion of manufacturing and shipment to IPP Greifswald 27 sets of mechanics for the polichromators,
2. **Task No 4** – Completion of bus bar connections between neighboring modules on MSP 5-1, MSP 1-2, MSP 4-5, MSP 2-3, MSP 3-4.
3. Total effort of IFJ PAN during 2007 - 2012 sum up to 160 FTEs.
4. Five IFJ PAN engineers have got a skill as Line Officers.
5. More than 50 engineers and technicians have been trained in the bus bar assembly process. The assembly process was very complex and demanding in terms of organizational and technological aspects.
6. The experienced personnel is currently involved in construction of the European XFEL at DESY, Hamburg and in the consolidation phase of LHC at CERN, Geneva.

7. Literature

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