In the framework of cooperation between the Max-Planck-Institut for plasma physics (IPP) and the Forschungszentrum Jülich (FZJ) essential work packages of the stellarator Wendelstein 7-X (which is presently under construction at Greifswald, Germany) have been taken over. For the superconducting bus system an overall concept of the project was elaborated with the goal to optimize working steps and to simplify the system assembly. The technical specifications are the basis for the design, construction, qualification, manufacturing and assembly of the bus and their appropriate supports. In order to compensate of the magnetic fields due to the bus currents and to facilitate bus assembly, a suitable bus topology was developed. No collisions with other parts, reduced space for integration and easy transportation were provided.

To facilitate and to check the development of a suitable topology for the bus system a 1:10 model have been ordered. Due to the developed topology data a complete set of bus lines have been build manually. On this model all steps for assembling and integration into the model have been tested successfully.
**Insulation development**

The insulation is one of the most critical components and had to be developed and tested in detail. In the case of a quench, the insulation has to withstand not only electrical fields of about 9 kV. It must take many thermal cycles from room temperature to 4K, tolerate high bending forces and must be operational for many years without failures. A series of insulation samples have been prepared and were examined due to highly sophisticated qualification procedure. FEM calculations have shown that due to magnetic forces and moments bending stresses of 182 MPa will occur. To simulate these stresses the samples have been cooled down to 77K and were bended by 28mm on a length of 0.5m to apply 200 MPa (including safety factor of 10%, see calculation). The bending cycles have been applied for 5000 times.

Sample length for calculation: \( l = 0.5\text{m} \)

Diameter for calculation due to rounding: \( D = 16.9\text{mm} \)

E-module of aluminium alloy: \( E = 70\ \text{GPa} \)

Stress to be applied: \( \sigma = 200\ \text{MPa} \)

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y_x = \frac{\sigma \cdot 2 \cdot l^2}{3 \cdot E \cdot D}
\]

necessary displacement for 200 MPa: \( y_x = 28.2\ \text{mm} \)

As the 5 layers will be bound wet into wet 5 insulation groups are necessary. The complete insulation must be finished within one shift. This picture shows several groups preparing the insulation of a 10m prototype bus line.

Due to the 3-dimensional shapes the insulation only could be realized manually. Two people will form a group where one applies the resin and the other will do the winding of glass fabric or capton foil.

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In the last step during manufacturing the insulation of each bus line will be examined carefully and must proof its functionality for years. Paschen measurements with 13 kV dc at 15 different vacuum levels as well as vacuum leakage
measurements will be performed. For realizing operational conditions with vacuum on the outside it will be covered by membrane bellows.

The picture shows the set up for paschen and vacuum leakage measurements

Manufacturing process
For manufacturing of the superconducting bus system the same superconductor as for the coils must be used. The 16mm x 16mm square cross section is very unsuitable to be bended in a 3-dimensional way. In order to facilitate the bending a rounding process to 17 mm diameter is used which is a compromise between remaining suitable wall thickness not less than 2 mm of the aluminium alloy but will facilitate the 3-dimensional forming. Measurements of the burst pressure of the rounded superconductor proofed that the minimum is still higher than 400 bar and well above of possible pressures in case of a quench which will be 170 bar.

Before any further treatment during manufacturing the superconductor must be protected against penetrating of dust and moisture from the air. Therefore both ends will be milled to a special shape and a special adapter will be welded to it.

For protection purpose the adapter can be closed with a screw or may be used to connect several testing equipments

For 3-dimensional bending a special computer controlled bending machine was bought and installed. Due to the bus line length of up to 15m an empty 3-dimensional space of about 8m in any direction is required. If the free length of the bended superconductor leaving the bending machine becomes larger than 3m it will deform its shape due to its own weight. To prevent this deformation its weight will be compensated by using a number of helium filled balloons. After a bended length of about 2 m a next balloon will be used. Furthermore the balloons will follow the movements of the superconductor during the bending steps.

Manufacturing hall with bending machine and a bus line dummy weight compensated with balloons

For final geometry checking of the bus lines and to compare it with the original construction a 1:1 model which also contains components of the mounting stand in Greifswald was designed. Each of the formed bus lines will be put into this model and possibly may be adjusted if necessary.

Model 1:1 with dummy coil segments and a bus line
Additionally measurements will proof that the superconductor even after adjustments will still fulfil all technical specifications. So it will be checked that:

- the maximum pressure of 200 bar for 15 min. can be taken
- the helium gas flow through the superconductor has not changed more than 10\% compared with the flow before bending
- the helium leakage rate must not exceed $10^{-9}$ mbarl/s per m

Part of the cooperation between the Max-Planck-Institute for Plasma Physics and the Forschungszentrum Jülich is also the design, manufacturing and delivery of support elements for the bus system. These supports are consisting out of holders which will lead the forces and moments to the central support ring or to the coil housings and the clamps which are the fixing parts to the bus lines. Due to mechanical requirements like tolerating of movements also the thermal requirements must be taken into account. To achieve most possible flexibility it was decided to use force loaded clamps to cover all mechanical loads. FEM calculations have shown that a design with stainless steel band will cover all conditions. In total 750 supports and 1500 clamps are necessary and will be manufactured.

In the following pictures a clamp and a support are shown as an example. The clamp is developed for two bus lines where one line can move due to different thermal expansion.

The support shown contains two ball bearings. This allows to align the holders to the direction of the bus lines to be supported. The thread in the centre of the holder is used to adjust the length of the holder. Several samples of holders and clamps have been build and will be tested at 77K in the near future.