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Butt Joint Tool Status: ITER-US LLNL-NMARTOVETSKY-01312007

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February 6, 2007

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LLNL

Memo

To: Distribution

From: Nicolai Martovetsky

CC:

Date: 01/31/07

Re: Butt joint tool status: ITER-US-LLNL-NMARTOVETSKY-01312007

Executive summary

Butt joint tool vacuum vessel has been built built at C&H Enterprise, Inc. Leak checking and loading tests were taken place at the factory. The conductor could not be pumped down better than to 500 mtorr and therefore we could not check the sealing mechanism of the seal around conductor. But the rest of the vessel, including the flat gasket, one of the difficult seals worked well, no indication of leak at sensitivity 1e-7 l*torr/sec. The load test showed fully functional system of the load mechanism. The conductors were loaded up to 2200 kgf (21560 N) and the pressure between the butts was uniform with 100% of the contact proved by pressure sensitive film. The status of the butt joint tool development is reported. This is the final report of the WFO contract with PPPL with the following parameters:

Customer Name : DOE-PRINCETON PLASMA PHYSICS
Agreement # : ICP006707-A
Agreement ID : 1023382
Project # : D110011
Agreement Expiration Date : 31-JAN-07

Introduction

ITER CS will use butt joints. We are building a tool and designed the butt joint details. This report describes some experience in preparation of the butt joint samples and discusses some details in the design. It also describes acceptance tests of the vacuum vessel at the factory.

First, let's remind the reader the butt joint design details.

Butt joint design details

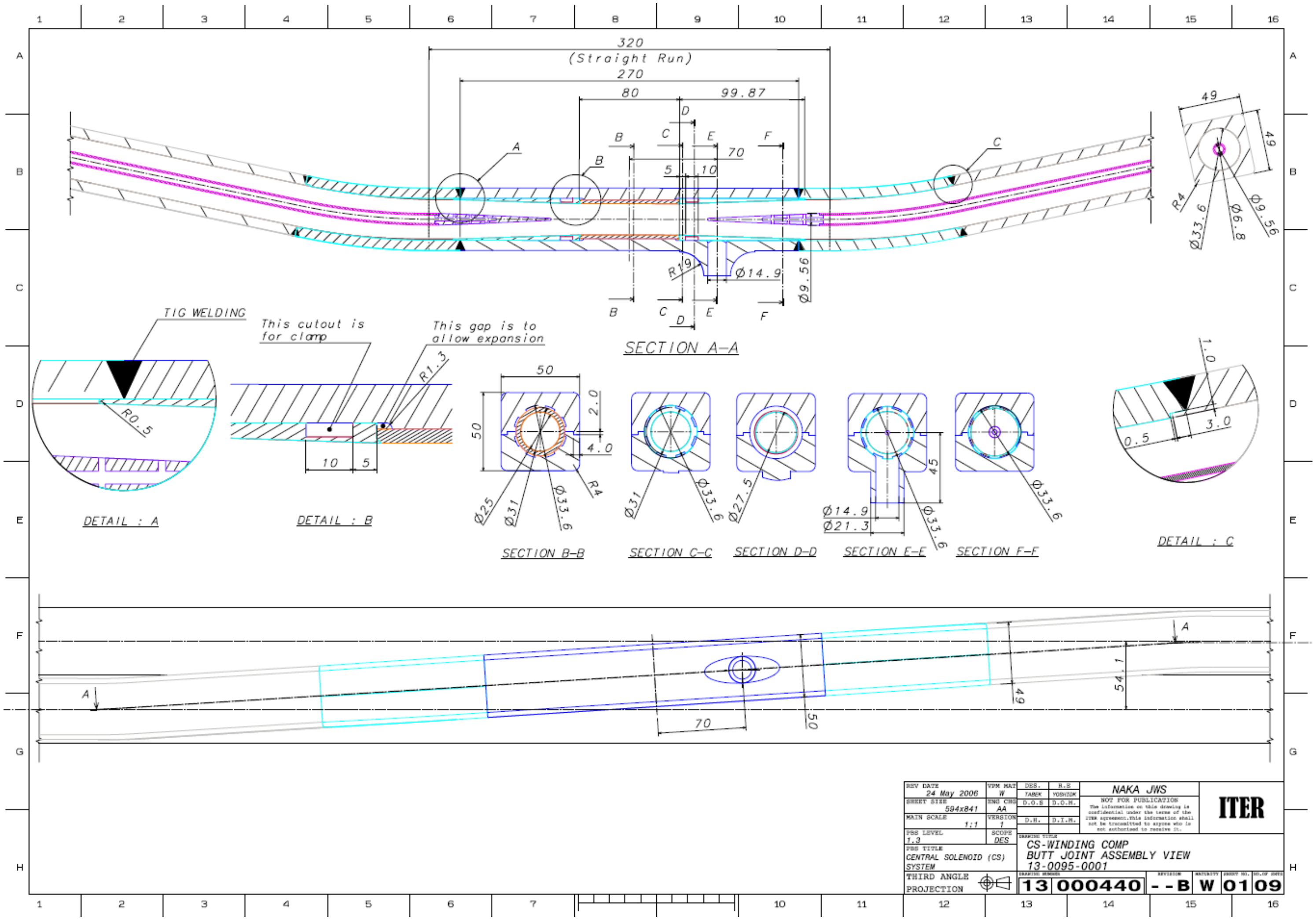


Fig. 1. Butt joint design details.

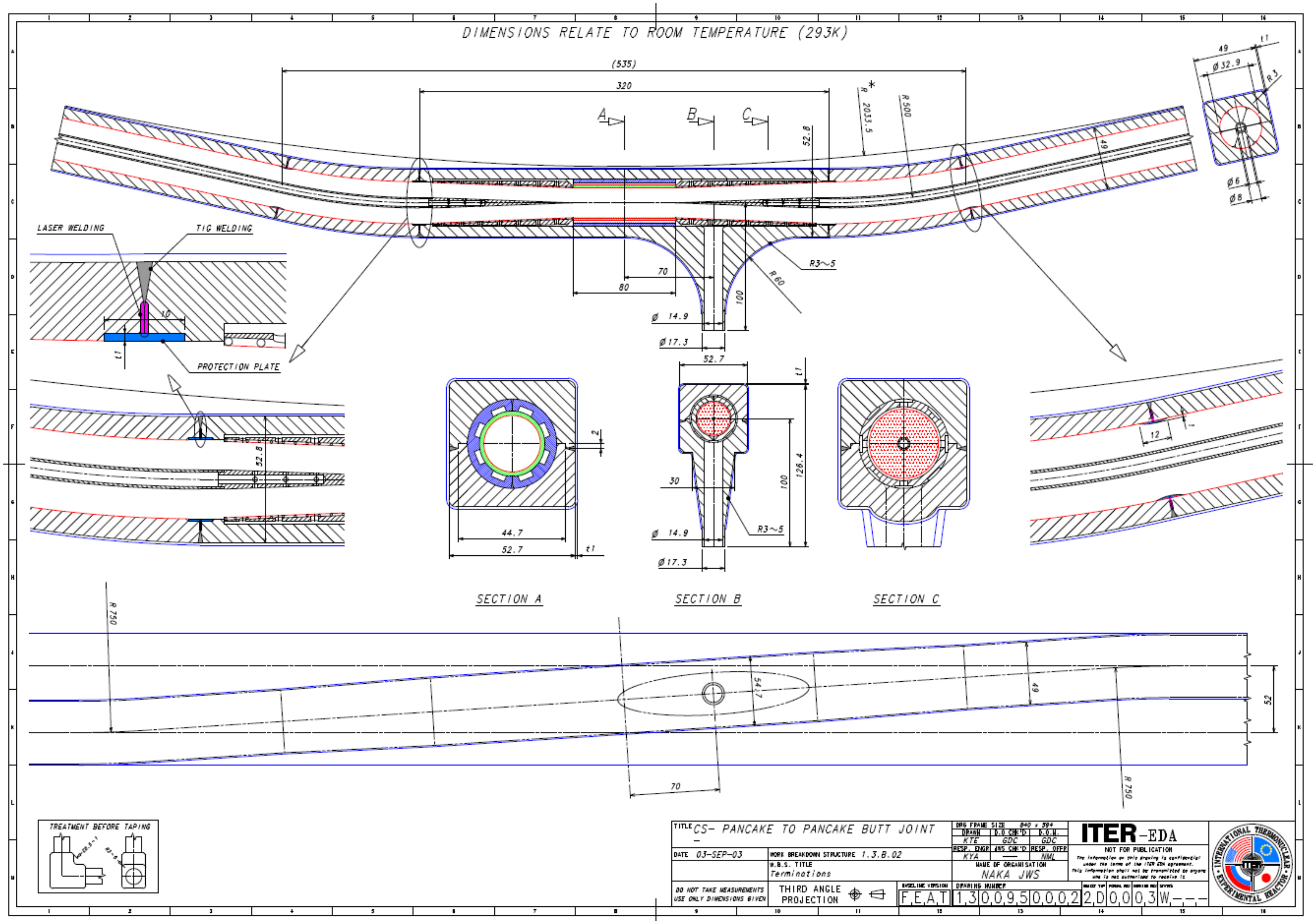


Fig. 2. Previous design of the butt joint weld.

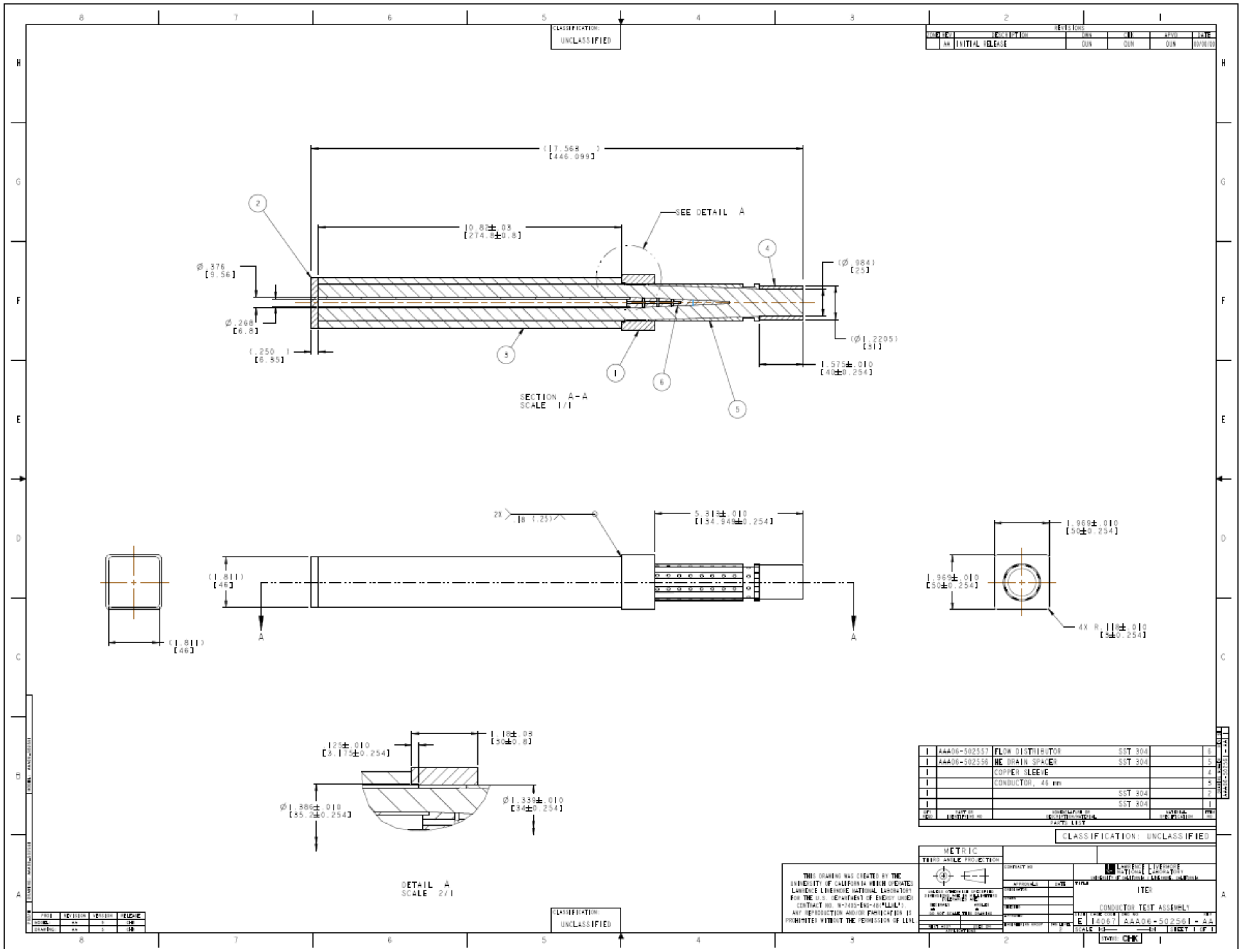


Fig. 3. Butt joint sample for the butt joint tool acceptance tests.

The tricky part of the butt joint is not only in the cable joint interface. It is also in the jacket welds, especially in the first welds made to the jacket of the transition piece, see detail C.

This weld is difficult. The weld as it is designed in Fig. 1 is done over the compacted cable. To protect the cable from the welding torch a lip is machined on the jacket. In the original ITER design, the cable was protected by a backing strip, see Fig.2. Such design was not practical. We can not machine a recess between the cable and the jacket to insert a backing strip. Inserting a backing strip hoping to compact the cable is impossible, the cable could not be compressed without a special and a very powerful tool. After my tests with the sample preparation I could not insert 1 mm backing strip between the cable and the jacket without damaging the strands. The cable is so tightly compacted that I could not even drive a pointed flat screwdriver to make a gap between the cable and the jacket to insert something. That was the CS2 CICC I was playing with, with a slightly higher void fraction than the CS, which will make the task even more difficult.

Thus, we can not have full penetration weld since the cable will get burned and most likely will contaminate the weld and/or will have partial penetration with a virtual crack and high stress. It is highly packed in the jacket. The partial penetration weld is used to provide some protective measure, although there is a little hope that the strands will not see the temperature rise below 210-230 C required by the specifications.

In addition to the welding heat problems we have a structural problem of this partial penetration weld – unacceptably high stresses. Peter Titus analysis [1] indicated that the stress concentration of such a weld is 4.6. This type of weld is called a “socket” weld in the tube welding industry and I became doubtful that such a weld should be used at such a high stress concentration factor.

I asked a confirmation of this assessment from two more well respected analysts and both of them gave although different results, but with also high stress concentration factor, from above 3 to up to 10 or so [2,3] and clearly growing at finer mesh. All three analysts ran ANSYS. I became suspicious that this is a singularity problem, mesh sensitive, which ANSYS can not handle in principle. L. Hagler search on the web resulted in a contact with an expert from Batelle welding laboratory [4]. He confirmed that ANSYS is not capable of handling such singularity problems and that the stress calculated by all three analysts is artificially high. He said that their laboratory developed a method of calculating stresses for such problems, found criteria for fatigue assessment of these cases. He also mentioned that treatment of such cases is so significantly different from what the ASME currently recommends that their procedure will be included in the next edition of the ASME B&PV code. He also made a proposal to analyze our problem and develop a list of analyzes and tests to qualify the weld.

Having this in mind and the fact that there is no easy way to insert a backing strip I came to conclusion that another possible way to insert the backing strip is to remove temporarily the central channel spiral at the point where the jacket is cut. By doing this I was able to pry a gap between the cable and the jacket. I think it is much more practical than other solutions. I recommend modifying the design of the jacket weld and the assembly procedure to eliminate the lip in the latest design, partial penetration and high stress concentration and introduce back the backing strip. The strip may have a groove to eliminate a direct contact of the strip with the jacket to improve the root pass. The weld will be done by a TIG process, full penetration weld. Such change in the design should remove necessity of extra effort in qualifying the partial penetration weld and proceed with the existing plan.

Butt joint samples preparation experience.

Since we did not have a real CS conductor we modified the CS2 conductor from the CSMC program. The design of the samples for the butt joint tool trials are shown in Fig. 3. We had to weld a piece of a jacket relevant to CS dimension and to make a representative cross section of the strands we had to eliminate (cut) 27 strands from each of the 6 last stage subcables.

We followed the procedure given in the specs [5]. We stripped off the conduit from the portion of the cable we needed to work with, see fig. 4.

Fig. 4. The CS2 CICC after the jacket is stripped off and the outer wrapped is removed.

Then we removed the wraps from the subcables and cut the spiral, as we should. After that, on one sample we untwisted all cabling patterns to continue an assembly, so they became parallel. On the other one we maintained the cabling. The purpose was to find out if parallel strands will allow a better compaction. In the end we could not see much of a difference in the sample preparation or compaction of the copper sleeve (see results below), so uncabling is not recommended, especially taking into account that it generates additional shielding currents.

Before installing a transition piece, which represents the CS conductor dimensions, I tried to see how feasible it is to insert a backing strip between the cable and the jacket, the problem I touched already. It turned out that the only way to do it is to remove temporarily the spring from the hole, by pulling the spring out, cutting it and shoving it back far enough in the hole that it would not be in the way at the edge of the jacket. This is a warning to CS CICC possible modifications– if we have a perforated tube, there might be a problem to do that, but since JAPT is making it, they have an access to the spring producer- Showa electric. When I removed the spring, I was able to pry open a gap not without some effort, but it seems doable to drive several sectors in the gap to install a backing strip.

After that we welded the transition piece on the conduit. This part o the sample preparation did not have to be relevant to the butt joint, but we tried to use this opportunity to get experience for the real butt joint. The transition was made in one piece and a little oversized hole to feed the cable through. This is a deviation from the current design, prescribing a clamp shell transition piece, as shown in Fig. 5. The rationale in such a change is to eliminate the longitudinal joint on the transition piece, since it introduces later a problem of connection of two joints on the jacket, one of which undergoes the heat treatment, another one does not. The penalty for this elimination of the weld is that the cable will be somewhat loose in the hole, since there is no mechanism to compact it after the assembly. One could have thought about driving a perforated tube to make cable to expand and get a support of the cable against the conduit wall this way, but this detail did not surface until now. We need to do some trade off study about if a solid transition piece makes better sense than going into trouble of having the split transition piece.

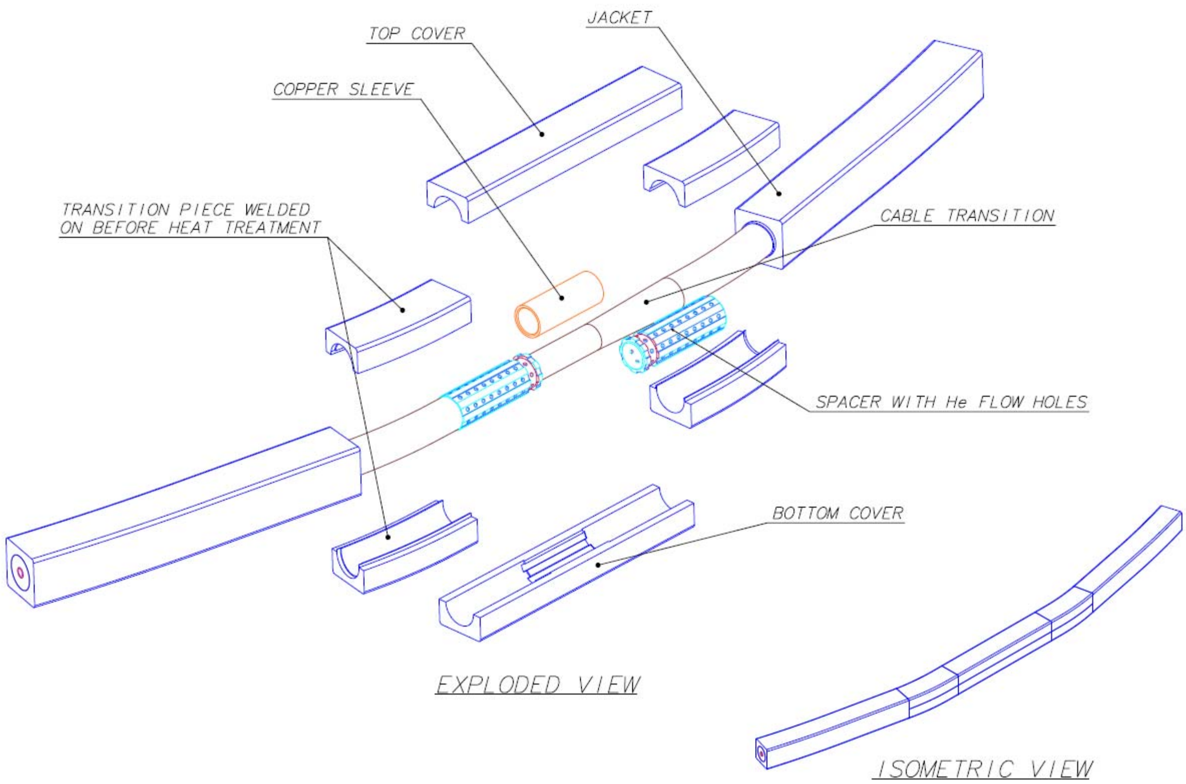


Fig. 5. Butt joint parts

The transition piece welded to the jacket is shown in Fig. 6.

Fig. 6. Transition piece welded to the CS2 conductor.

The next operation we did was inserting the internal flow distributor. For the conductor where we uncabled all the strands it took a while to find the location of the central hole to insert the flow distributor. Fig. 7 shows how the cable with fanned strands looks like.

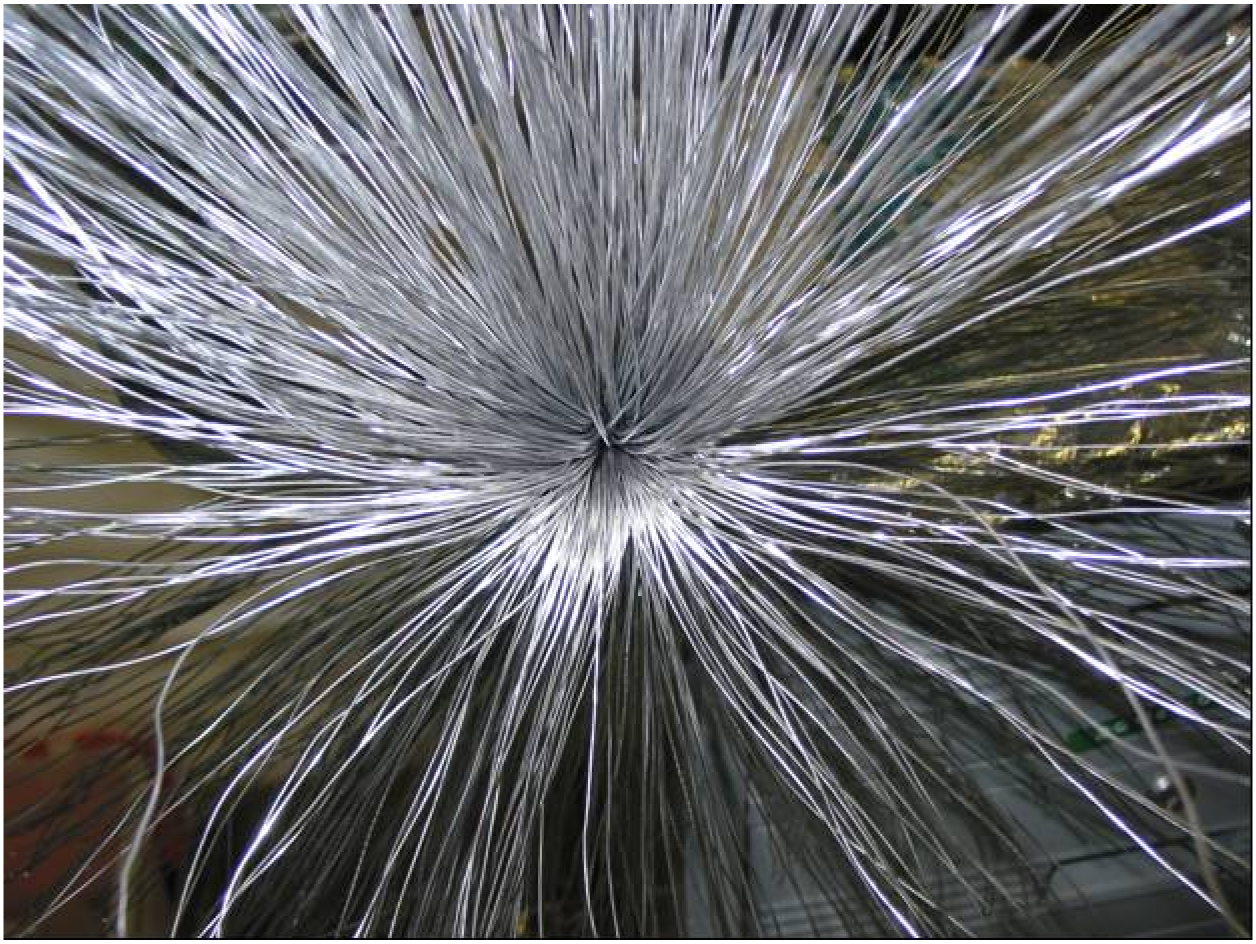


Fig. 7. Cable with the spread strands.

Fig. 8 shows the flow distributor inserted.

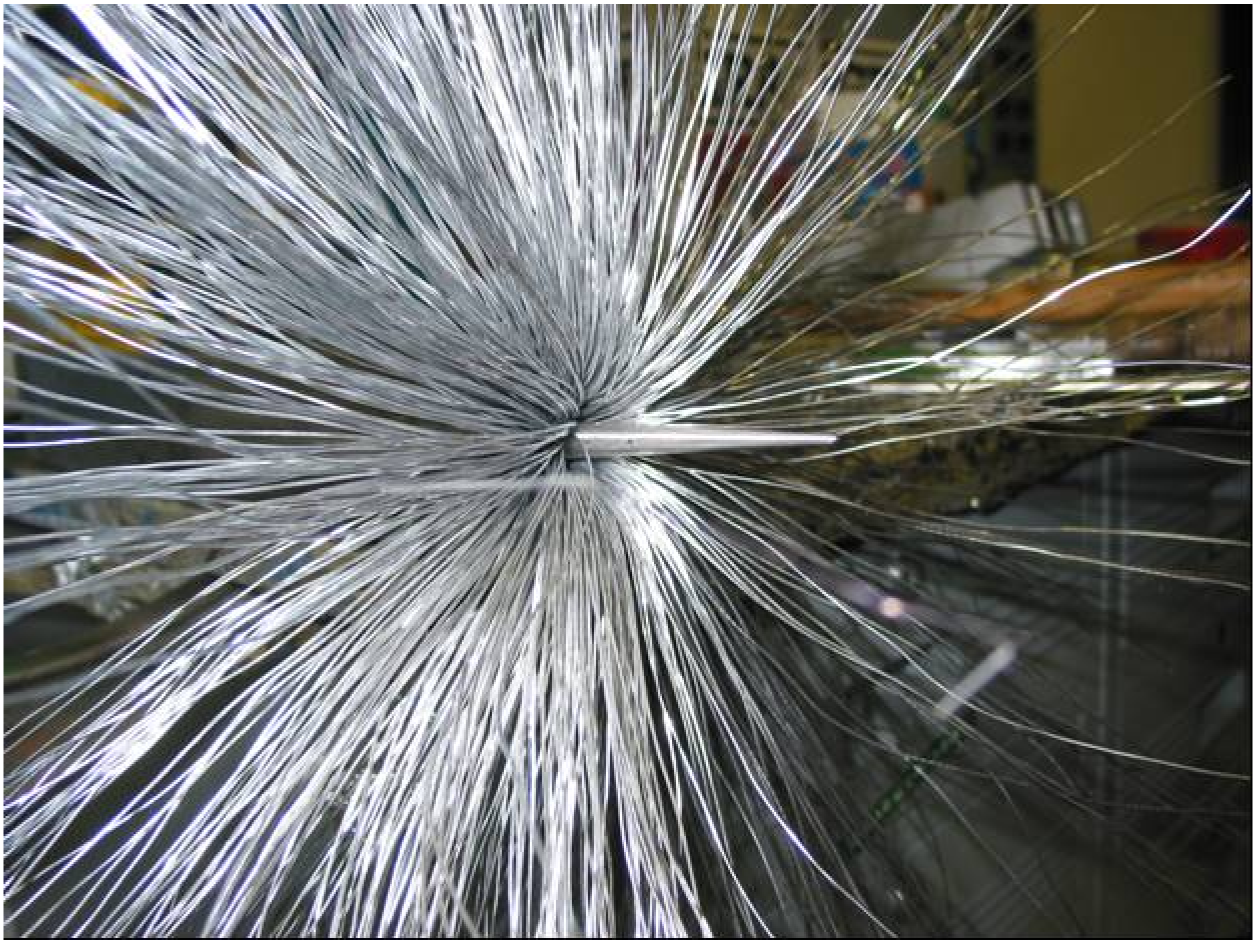


Fig. 8. Inner flow distributor inserted in the cable central channel.

Fig. 7 and 8 once again illustrate that undoing the cabling is not advisable.

The next step in the sample preparation was to install the outer flow distributor.

This step did not go well at all. The flow distributor is made of 304 steel. The inner hole is conical and the outer diameter is constant, in other words the OD surface is cylindrical, with grooves and holes. The hope was that the slight tapping on the distributor will overcome friction.

That hope did not come true. The distributor did not want to go, see Fig. 9.

I decided to simplify the procedure by splitting the distributor in two halves and then put it on and compress it with the band clamps. It did not work – significant number of strands got caught and it was not humanely possible to squeeze it all without some strands caught in the crack. I ended up cutting more strands from the cable underneath the flow distributor. I left all the strands underneath the copper sleeve to preserve the compaction of the sleeve.

This is OK for the sample, but for the real conductor something needs to be changed. For the future trials I decided to modify the flow distributor. From now on I will use the flow distributors with the inner diameter cylindrical and outer diameter conical and after I put it on I will compact it with my crimping tool. Due to my relocation this step will have to be demonstrated later.

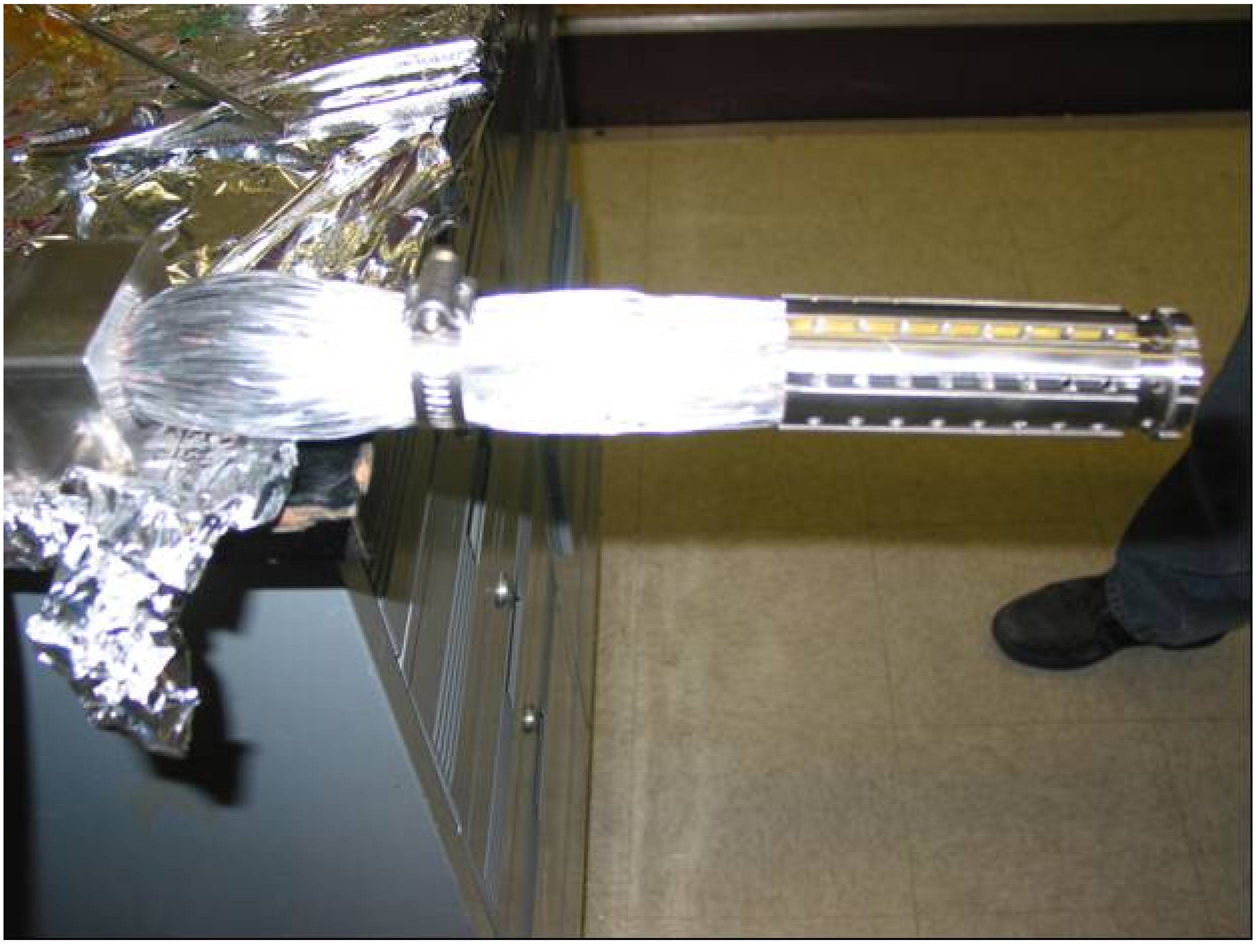


Fig. 9. The flow distributor is stuck on the cable and would not go.

The idea of a new flow distributor, without holes and gooves for simplicity is shown in Fig. 9a.

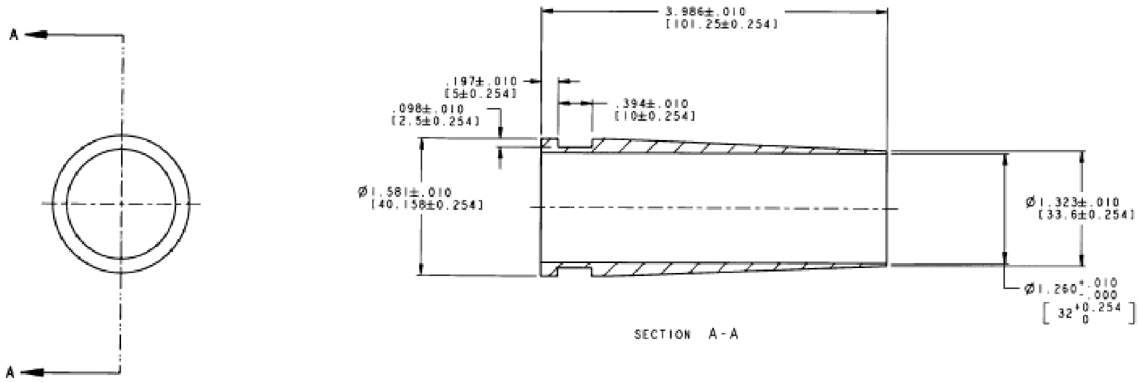


Fig. 9a. Modified flow distributor (has no holes and grooves to try for feasibility).

Compaction of the copper sleeve with the cable went smoothly. We used the crimper we bought for this purpose a year ago, shown in Fig. 10. The crimper is capable of applying of 140 t of force to compact the sleeve.

Fig. 10. Hydraulic crimper used for compacting the cable in the copper sleeve.

The final compaction of 31-31.1 mm was achieved by applying all 140 t of force of the die, which at the final squeeze was not fully closed, which illustrates that the compaction could not be increased with this tool. The cross section looks acceptable to me and at a glance corresponds to 5-8% required void.

I doubt that the void will get smaller with higher compaction force. Before it closes I'd imagine we'd see a great deal of deformation in the strands, which we would not like fearing breakage of the diffusion barrier and filaments deformation. The cross section of the compacted cable in the sleeve is shown in Fig. 11, which is intentionally a little overexposed to emphasize the voids.

For the purpose of the sample preparation we did not buy a tool yet to cut the sleeve with the cable. Instead we used an EDM to make a clean cut. The disadvantage of this is that the sample needs to be placed into a water bath, In real conditions, we can not do that for several reasons. We will use a diamond saw, used for preparation of the slices for metallographic analysis.

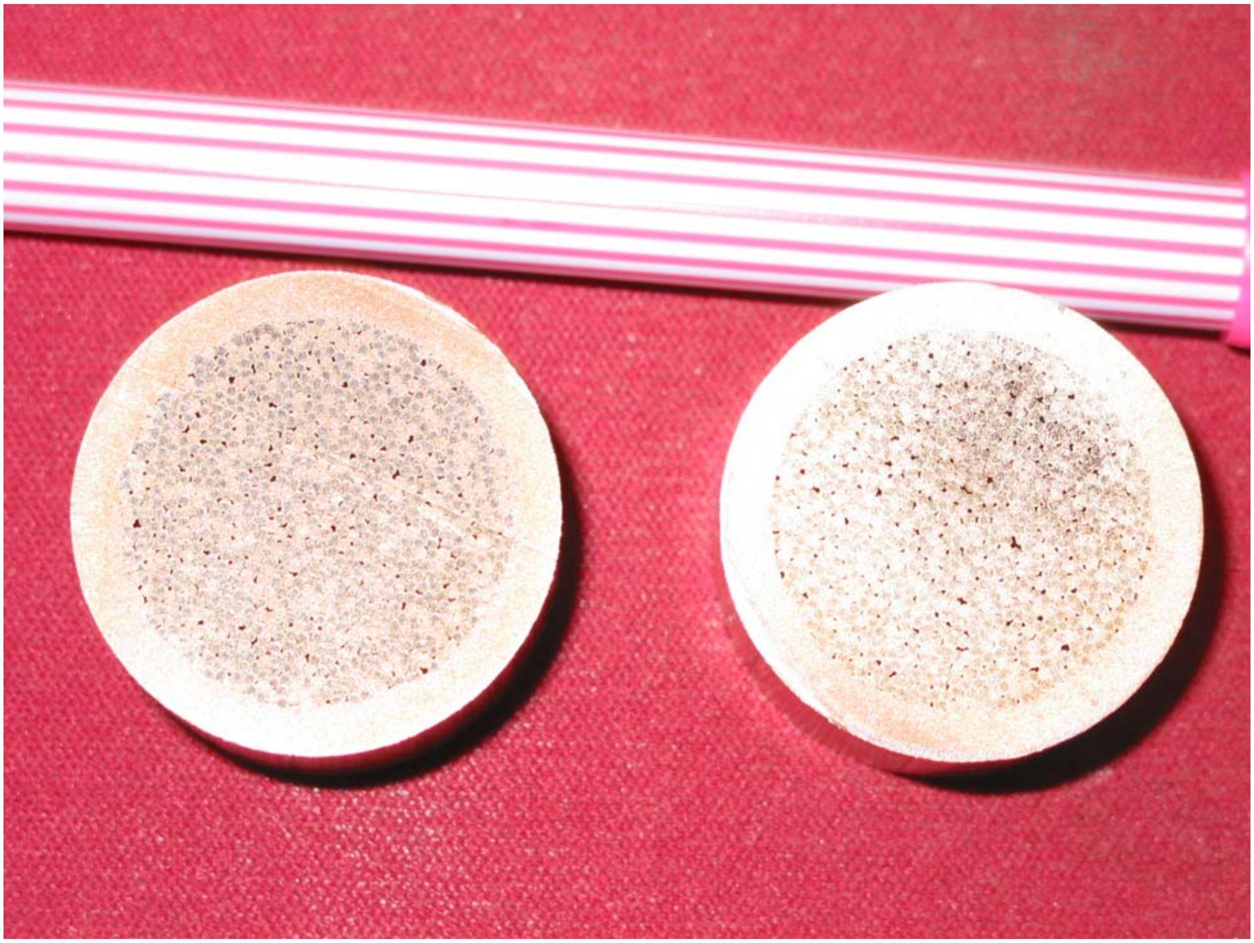


Fig. 11. Compacted and sliced cables in the copper sleeve.

Leak checking of the vacuum chamber.

Butt joint vacuum chamber was built by C&H Enterprise in Fremont, CA.

Principle schematic of the butt joint tool is shown in Fig. 12, which gives a CAD cross section of the tool with the conductors prepared for butt joining.

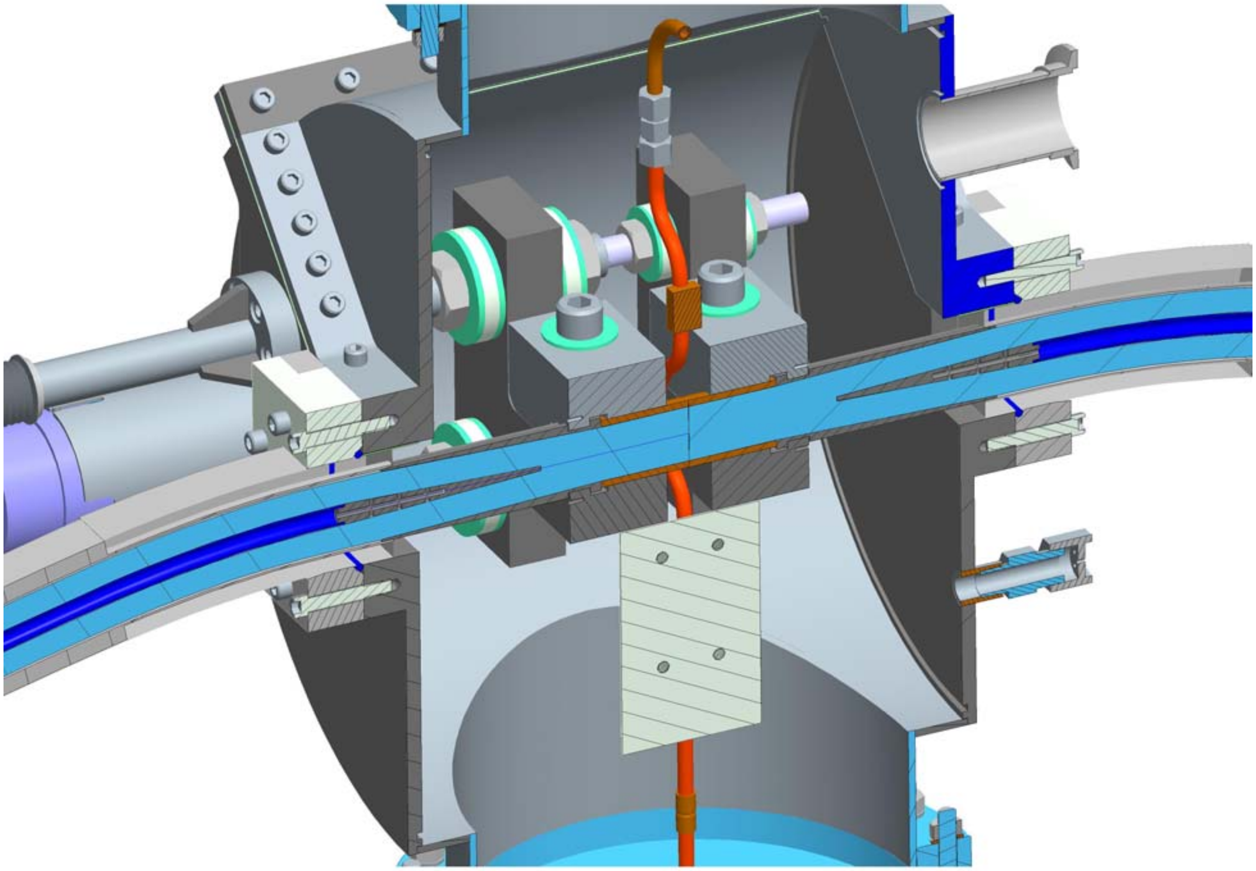


Fig. 12. Cross section of the vacuum chamber.

Fig. 13 is a photograph of the inside of the vacuum chamber tool with the samples.

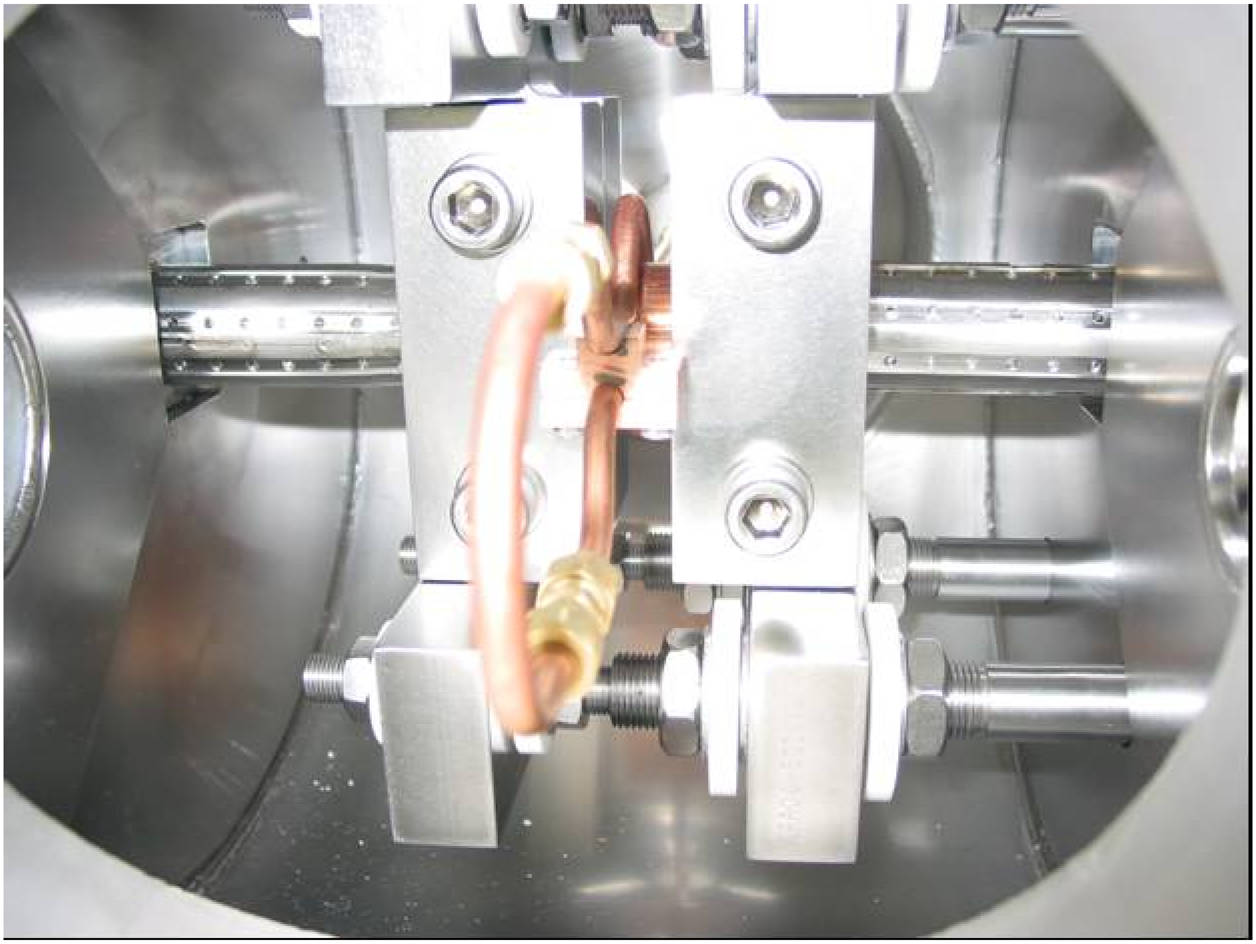


Fig. 13. Inside the butt joint tool.

Since installing a power supply and control system at the factory was not a viable option, we could not run a full acceptance test of the butt joint for many reasons.

The acceptance tests at the factory included leak tests and load tests.

Leak test

The samples to be butt joined were given to a company next door from C&H in Freemont for cleaning and drying. After receiving them, the samples were installed and the chamber sealed and connected to a vacuum pump with a leak detector.

We pumped on the vessel and discovered several problems.

First, the O-ring around the conductors leaked badly. A close look revealed that the O-ring cross section is too small, see Fig. 14.

Fig. 14. The O-ring cross section is too small to seal around conductor.

To eliminate this problem we used a duct seal putty to seal the conductor. However it did not fix the problem. The pressure did not go under 500 mtorr, which was not even sufficient to turn on the mass spectrometer leak detector.

I suspected that the area of leaking could have been the flat gasket between the cover and the vessel.

We used the same putty to seal the cracks and bolts compressing the cover to the vessel. That did not help either – nothing changed. The other suspects are the welds, but the appearance of the welds was very good – one could appreciate high quality of the C&H welders.

We assessed all suspicious areas where the leak could go through and thought that the most likely area of the leak was the viewport and the plate with the induction heater feedthrough. We decided to use a constriction valve at the inlet to the leak detector to create sufficiently low vacuum at the mass spectrometer that would allow us use leak detector.

We had a weak and uncertain indication that the 10 inch viewport seal was leaky. Sprayed helium around the seal caused a signal in the leak detector most of the time with some delay, but the reproducibility was not that great. The viewport was sealed with the viton O-ring – reliable enough seal in usual circumstances. We decided to replace it with a more reliable copper gasket with the knife edge seal.

Next day we did replace the viton O-ring with the copper gasket, but the vacuum did not improved. Also we could not find any indication of helium leak there anymore.

We decided to use the duct putty to seal all the welds, cracks with O-rings, see Fig. 15. The vacuum was the same.

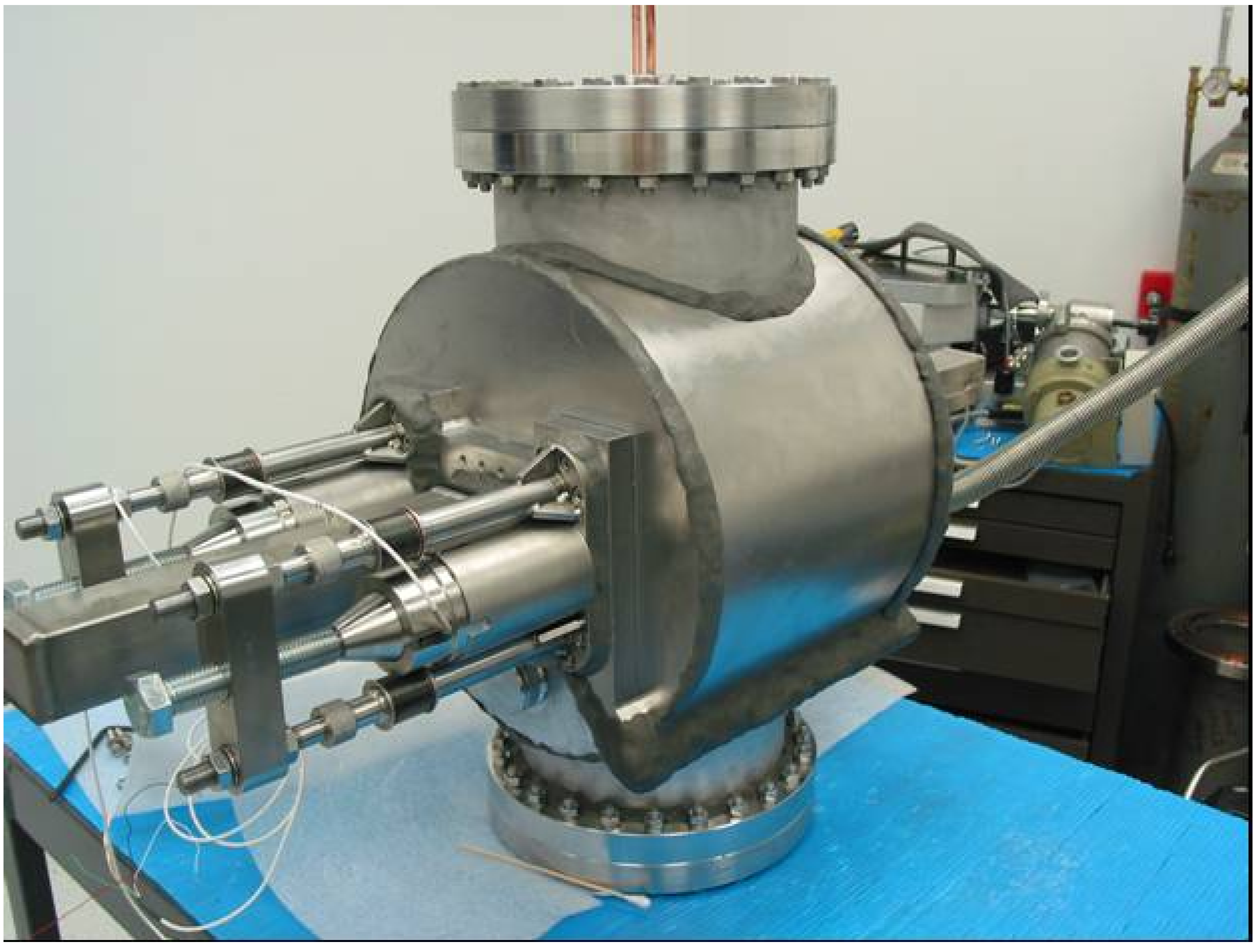


Fig. 15. The vessel with sealed seams.

After that it became clear that there is something wrong with the conductors.

We dismantled the chamber, removed the conductors and sealed the openings with plates and duct seal.

That immediately brought the vacuum to several millitorr and allow leak checking, which showed that there were no detectable leaks at the sensitivity of 1e-7 torr*liter/s.

Apparently the cleaning of the samples was not sufficient. Later we discovered that the drying was done at 110 F for 2 hours, which turned out to be insufficient, the samples had plenty of moisture left inside. We tried to pump on the conductors only and were not able to pump them down to better than 500 mtorr.

Thus, in the leak test we showed that the vessel is leak tight, but we were unable to verify the most critical seal – around conductor due to wron O-ring size. We will have to verify it later during debugging of the tool.

Load test

The load test was conducted to demonstrate that we can apply required force. At required 25 MPa and 31 mm OD, the required force is 17.4 kN or 1.77 metric tons of force.

We decided to go up to 2.2 tons, since we were applying force at RT, instead of 750 C which will be necessary during butt joining.

We put a copper foil 100 microns thick and a sheet of a pressure sensitive film in between the butts of the samples to monitor quality of the contact.

We successfully applied 2.2 force (see Fig. 16) which shows readings of the load cell indicators.

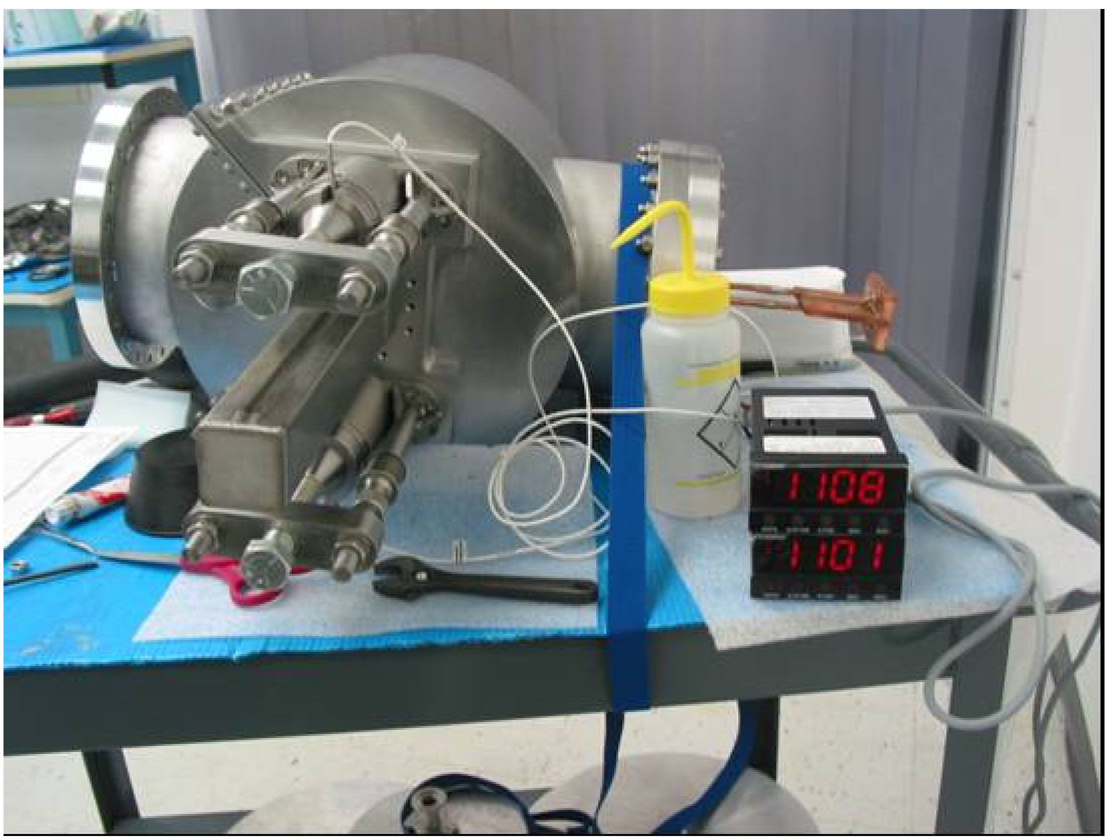


Fig. 16. Loading test, force on the interfaces is 2.2 tones, about 22 kN.

After dismantling the load we discovered that one of the ceramic washers cracked. It should not have – the claimed strength of the washer is about 7 times more than the average pressure on it. I contacted the company for suggestions, but they could not offer any, claiming it should not have happened, the ceramic is strong to take this load easily.

I ordered replacement washers and received them, the reason for crack remains unknown – either it was caught in the tread somehow or was defective from the start.

Control unit

The butt joint tool is a complex device with many subsystems and functions.

Main elements are:

Vacuum chamber

Induction heater

Vacuum system,

Loading system

Cooling system

Data acquisition system

Instrumentation

Control system

A functional schematic of the butt joint tool is shown in fig. 17.

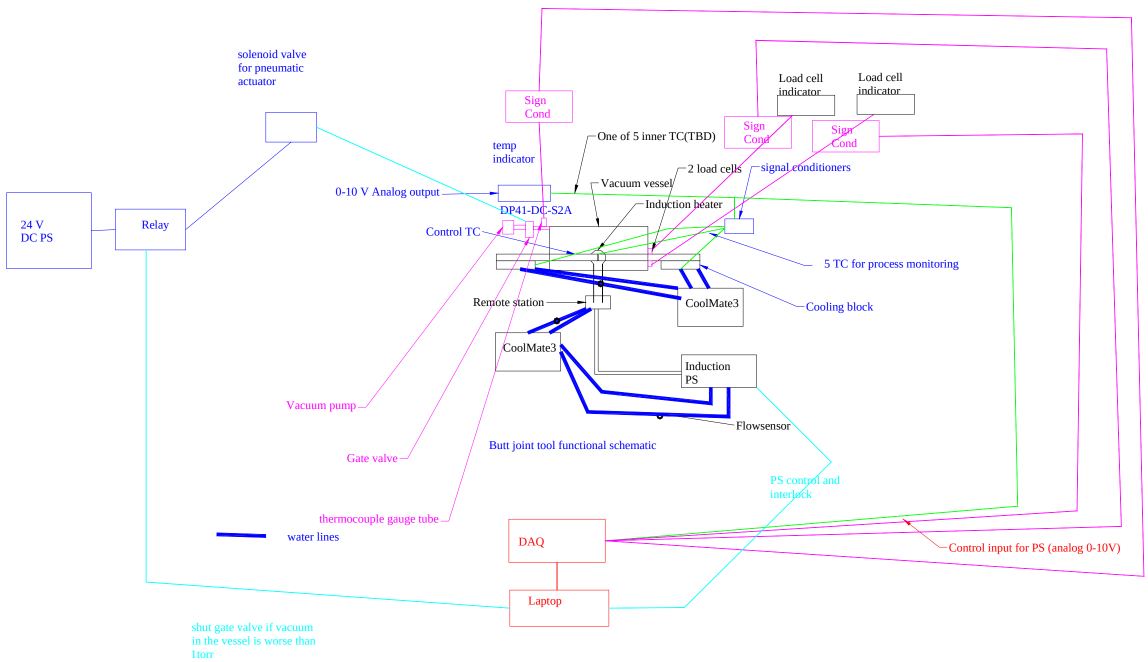


Fig. 17. Functional diagram.

The requirements I for the control and instrumentation are given below:

As a minimum, I need the following safety and control features:

1) Water leak, even small should switch the Power Supply (PS) off immediately, since water leak can develop inside the vacuum chamber (unlikely, still I have to protect against it). That will cause immediate steam, pressure build up. I have a pressure relieve valve, but I worry about electrical shorts and flooding the chamber. I also need to do something to protect my vacuum pump against events like this. That will be a gate valve controlled by the computer. I think it would be even better if I have a vacuum gauge indicator with relay which will activate the actuator when the vacuum gauge reads higher level than a threshold (TBD, assume 1 torr at the moment). Many indicators have built in relays and programmable point when the relay closes. It is better than control it on the computer, since allow operation even when the computer is off line.
2) Flow switches are already connected to the power supply and have interlocks, no need to worry. When the flow stops, the PS shuts off. I do not need necessarily to monitor those, but if RS232 automatically reads the interlock status, I might as well store their status versus time as well

3) I will have 7 thermocouples maximum: two thermocouples are next to the viton O-ring outside the vessel and 5 are inside. One of those 5 will be a control TC, the rest are for

monitoring. I plan to use a specifically dedicated temperature indicator for the control TC that I'd know the temperature regardless of the computer.

4) I also want to see load cells reading and vacuum independently of computer.
5) As far as control goes I want to heat up the butt joint after I have vacuum established by turning on the power supply. I have no specific requirements on how fast the temperature grows, in principle, as soon as possible may be OK, unless I learn that there should be some profile. Then I need to reach and keep 750 C +/- 5 C measured by the control TC for say 70 min, then turn off the PS and let it cool off. The PS has built in timer, but it would be nice to have it computer controlled.
6) Summary of the interlocks should be on the following parameters (this is the maximum I can think of)

a) water flow – shut PS off if there is no flow or a leak (already built in the PS and provided by the PS vendor)
b) vacuum in the chamber – shut it off at a certain threshold (say 1 torr)
c) short – shut off the PS
d) shut off if the PS if temperature near seals goes too high (TBD, about 220 C)
c) Gives sound warning if load cell readings are below or higher than acceptable, but no action

The channels I need to store by the DAQ:

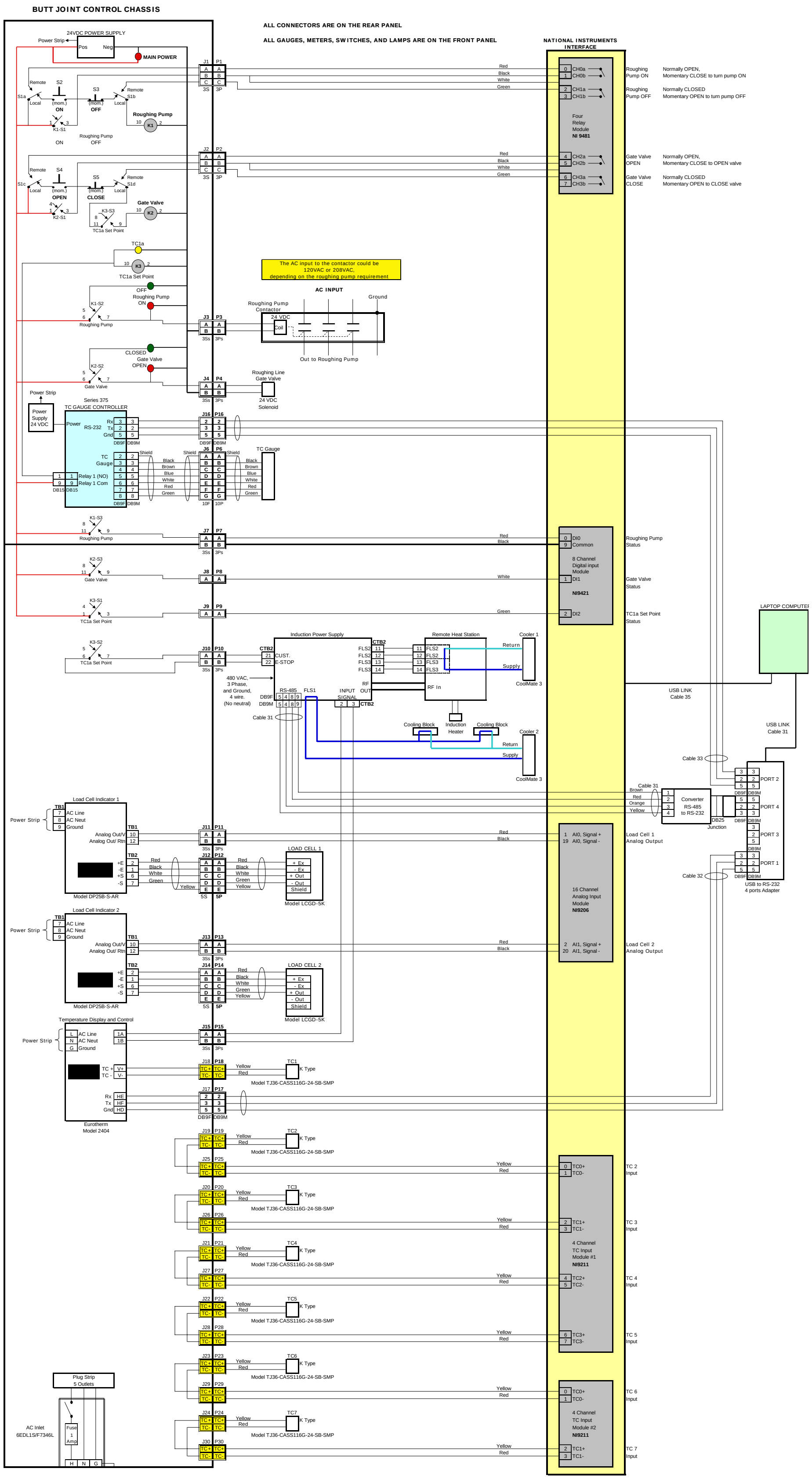
1) 7 thermocouples
2) 2 load cells
3) Vacuum gauge readout. We talked about ion gauge, but my vacuum requirement is better than 0.6 Pa=$6*10^{-3}$ mbar=$6*10^{-3}$ torr=6 microns of Hg. The ion gauge is good for 1e-3-1e-10 torr, thermocouple is good for 1e-4 torr. I need a vacuum controller, which would make an interlock with the induction heater PS and monitor pressure above several millitor.

4) State of interlocks .

The data acquisition system will log all the process parameters and control the required temperature.
The I&C is based on the National instruments module and LabView software.
The wiring diagram of the controls is given in the diagram below.
After the unit was assembled I verified that the data acquisition system monitored and record the temperature readings, vacuum and loads. I could not check the Power Supply for obvious reasons, so the I&C system was not completely debugged, which will be done at the facility when the butt joint toll will be installed and debugged.

ITER BUTT JOINT
CONTROL CHASSIS AND EXTERNAL CONNECTIONS
WIRING DIAGRAM

9/20/06
R. GEER
Updated 01/06/07



Conclusion

Butt joint tool is in a final stage of component completion. Early in March 2007 we plan to start assembly of the tool at an Oak Ridge vendor site.

The tool is leak tight, capable of applying load, I&C is complete but needs debugging with the induction power supply.

References

1. P. Titus, Memo to: Nikolai Martovetsky/Chen Yu Gung

Date: June 13 2006, Subject: Jacket Butt Weld Design/ Stress, ITER/US/MIT/PTitus/06-13-2006-1

2. E. Bobrov, September 12, 2006, private communication

3. L. Hagler, Oct.2006, private communication

4. Pingsha Dong, Center for Welded Structures Research

BATTELLE, Columbus, OH, dongp@battelle.org, www.battelle.org/verity

5. ITER CS specifications, draft, version VIII, June 2006.