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Butt Joint Tool Commissioning

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December 7, 2007

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Memorandum

To: Distribution

From: N. Martovetsky

CC:

Date: December 06, 2007

Re: Butt joint tool commissioning

Executive summary

The butt joint procedure was verified and demonstrated. The tool is capable of achieving all specified parameters. The vacuum in the end was a little higher than the target, which is not critical and readily correctable. We consider, tentatively that the procedure is established. Unexpectedly, we discover significant temperature nonuniformity in the joint cross section, which is not formally a violation of the specs, but is a point of concern. All testing parameters are recorded for QA purposes. We plan to modify the butt joining tool to improve its convenience of operation and provide all features necessary for production of butt joints by qualified personnel.

Introduction

ITER Central Solenoid uses butt joints for connecting the pancakes in the CS module. The principles of the butt joining of the CICC were developed by the JAPT during CSMC project. The difference between the CSMC butt joint and the CS butt joint is that the CS butt joint is an in-line joint, while the CSMC is a double joint through a hairpin jumper.

The CS butt joint has to carry the hoop load. The straight length of the joint is only 320 mm, and the vacuum chamber around the joint has to have a split in the clamp shell. These requirements are challenging. Fig.1 presents a CSMC joint, and Fig.2 shows a CS butt joint.

Fig.1. CSMC butt joint which joins two layers by a hairpin jumper, so two interfaces are in the joint. The joint interfaces are difficult to see after bonding. They are in the middle of the copper sleeves (Courtesy of Y. Takahashi).

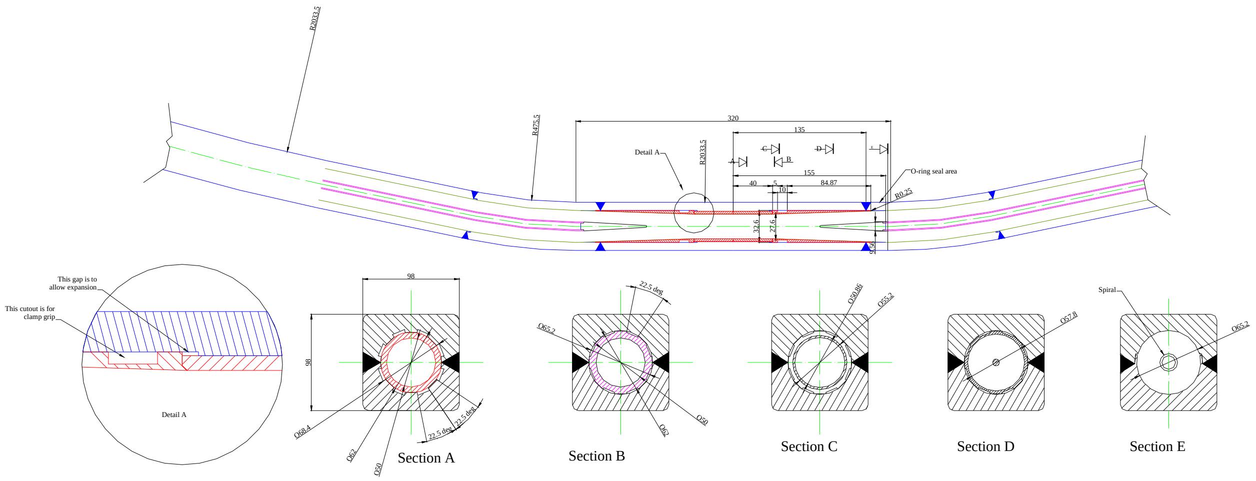


Fig. 2. Cross section of the CS butt joint (the outlet is omitted for simplicity)

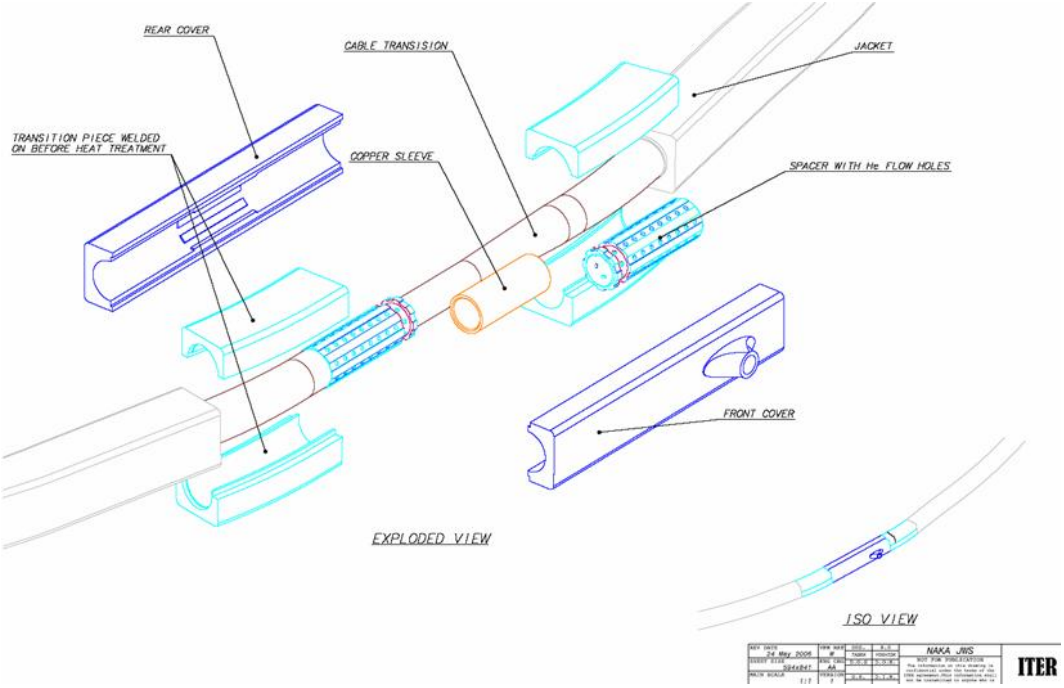


Fig. 2a. Exploded view of the butt joint. Note that the copper sleeve shown in the figure consists of two sleeves bonded together using a diffusion joining process.

Parameters for the joint bonding

JAHT specified preliminary parameters of the conditions for the butt joint formation as follows: 750 C for 70 min at 25-30MN pressure and 5 mtorr vacuum. This became a tentative ITER specs. It turned out later that 750 C claimed by JAHT as a process parameter is related to the temperature on the butt joint clamp, not on the copper sleeve itself. That will be discussed below.

Description of the butt joint bonding system

During the butt joint development project, US IPO designed and built a butt joint bonding system shown in Fig. 3 and 4.

Fig.3. Butt joint bonding system. The vacuum vessel (Steve Kenney is looking inside) and the I&C rack (foreground) are seen. The turbo pump (SS cylinder right behind the bottle with acetone on the cart) is attached to the vacuum vessel through the isolation in-line valve (black cylinder sticking up). A roughing pump is on the floor (black on the plywood, to the right from the rack). Two water cooling stations are next to ventilation duct (on the floor, black).

The induction power supply and heating station are seen in Fig. 4.

Fig. 4. The butt joint joining system shown from the side of the power supply and the remote station, connected to the induction heater coil.

A closer view of the vacuum vessel is shown in Fig. 5; the viewport is open, showing the heater coil.

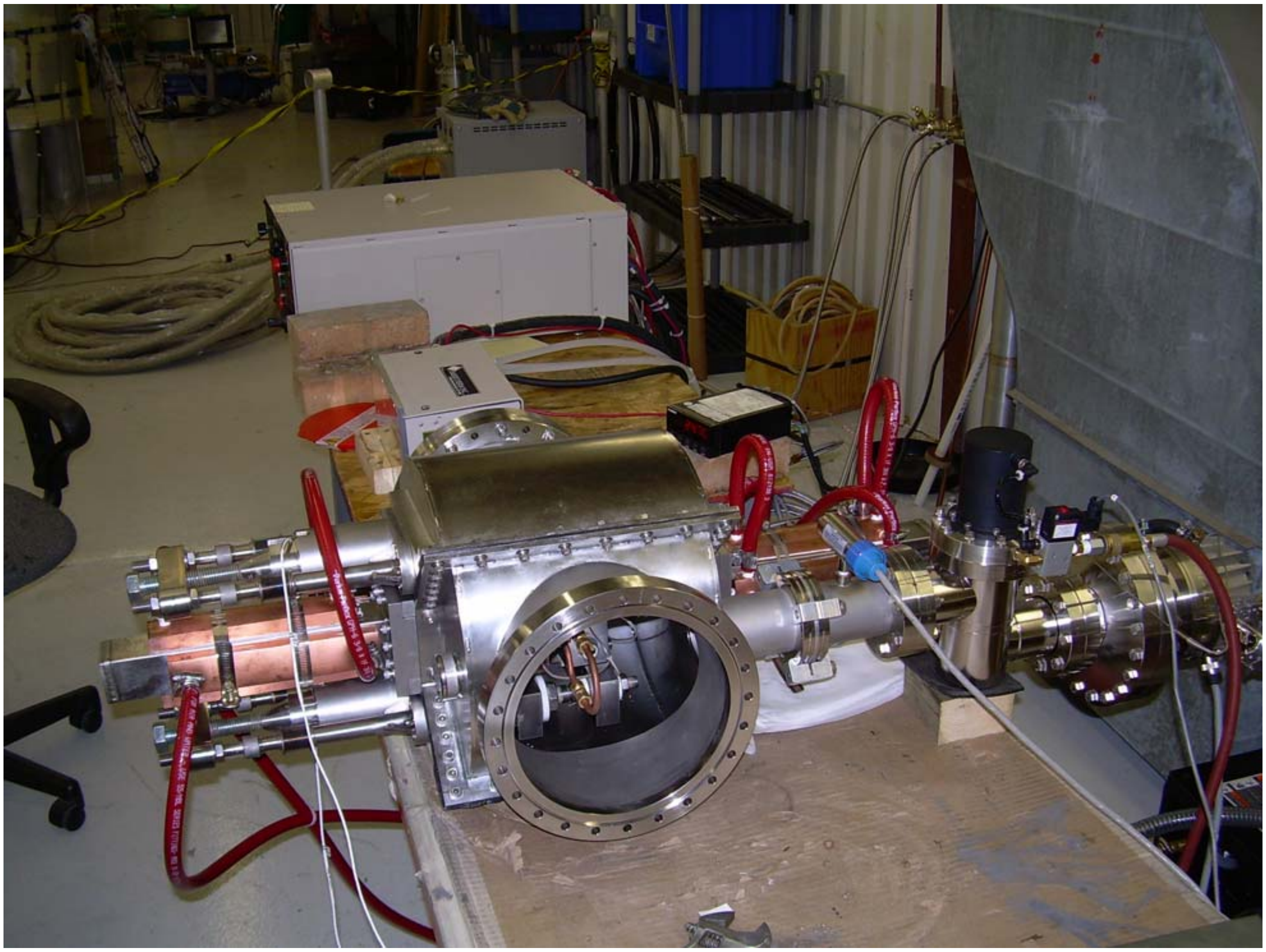


Fig. 5. Butt joint vacuum vessel. Copper cooling blocks outside the chamber are seen attached to the conductors to be joined.

The instrumentation and control rack was designed and built in order to control the process and record the data during the process. In fabrication of the ITER CS it will not be possible to test the joints for resistance and strength. The approach we selected is to establish the process, qualify performance of the joints fabricated by the process, and then reproduce precisely the fabrication conditions in production of the CS joints. The front panel of the rack is shown in Fig. 6. Descriptions of the controls and displays are given in the table below.

1	Load Cell Indicators. Display load cell pressure.
2	TC Gauge Controller. SP1 set to -100mT, SP2 set to -50mT.
3	Induction Heater Power Supply Temeperature Controller. It is controlled by LabView.
4	Butt Joint Chassis Control mode switch. FRONT PANEL position allows control from the front panel switches on the chassis. COMPUTER position allows control from the laptop computer.
5	Heater Enable Switch. Must be in the ON position to allow computer control of the Induction Heater Power Supply.
6	Main Power indicator. Lamp is ON when the main power is turned on. The Main Power switch is located on the AC inlet connector on the rear panel.
7	Valve Interlocked indicator. The yellow lamp is turned ON when the pressure goes below SP1 (100mt). Set point 1 is set to -100mT. The lamp will go OFF when the pressure goes back above 100mT and the valve will close and the Induction Heater will shut OFF.
8	Valve OPEN for Pump Down Switch and Lamp. The OPEN switch is to be pushed once to begin pumpdown. After the pressure goes below SP2 (50mT) this switch is disabled. The red lamp is ON indicating the valve is OPEN during pump down.
9	Valve Control for Pump Down OFF Switch and Lamp. The CLOSE switch can be pushed to CLOSE the valve during pump down. After the pressure goes below SP2 (50mT) this switch is disabled. The green lamp is ON when the valve is CLOSED.
10	Valve Control When Interlocked OPEN Switch and Lamp. This switch is enabled when the pressure goes below SP1 (100mT). When interlocked the valve can be opened by pushing OPEN. The red lamp is on when the valve is OPEN when interlocked.
11	Valve Control When Interlocked CLOSE Switch and Lamp. This switch is enable when the pressure goes below SP1 (100mT). When interlocked the valve can be closed by pushing CLOSE. The green lamp is on when the valve is CLOSED.

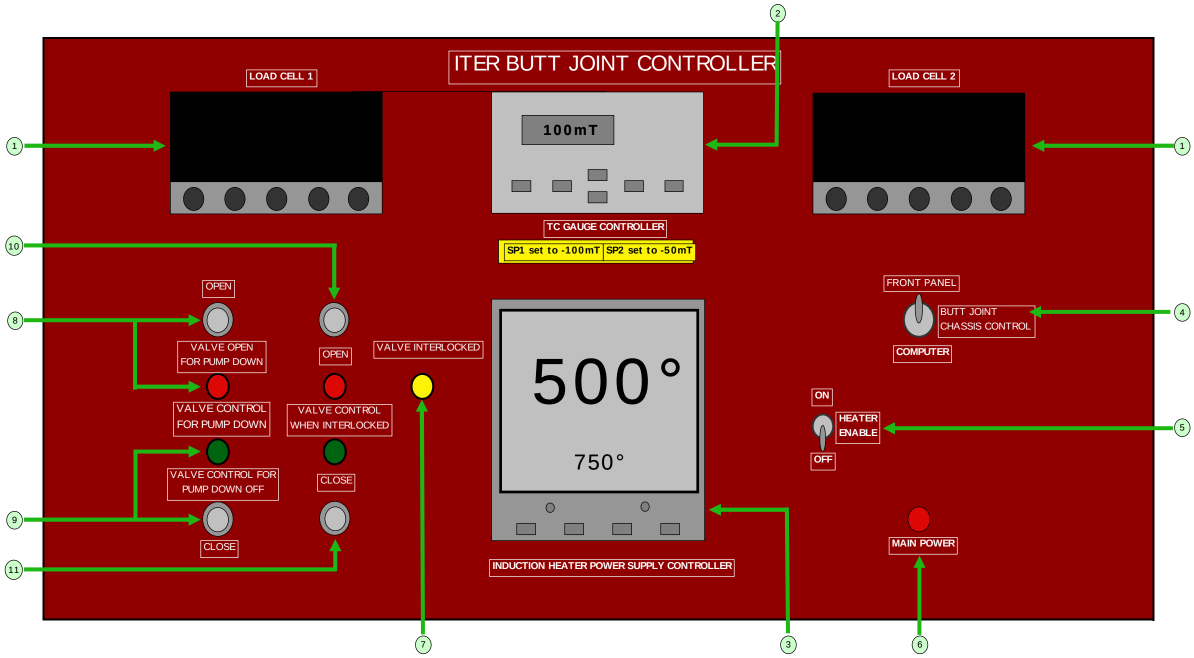


Fig. 6. Front panel of the I&C rack.

The temperatures of the butt joint and the conductor are monitored with seven thermocouples that are read and recorded by a Labview based DAS (data acquisition system). Five thermocouples are located inside the vacuum vessel and two are outside. The most important are the thermocouples located in the vicinity of the butt joint.

Fig. 7 shows the arrangement of the thermocouples as it was from the end of July 2007 until we broke and rearranged thermocouples in early October. In these later runs the thermocouples were reassigned, as discussed later in this memo. For the future we intend to maintain the arrangement of odd-numbered thermocouples on the right (looking in to the vessel through the viewport) and even numbers on the left.

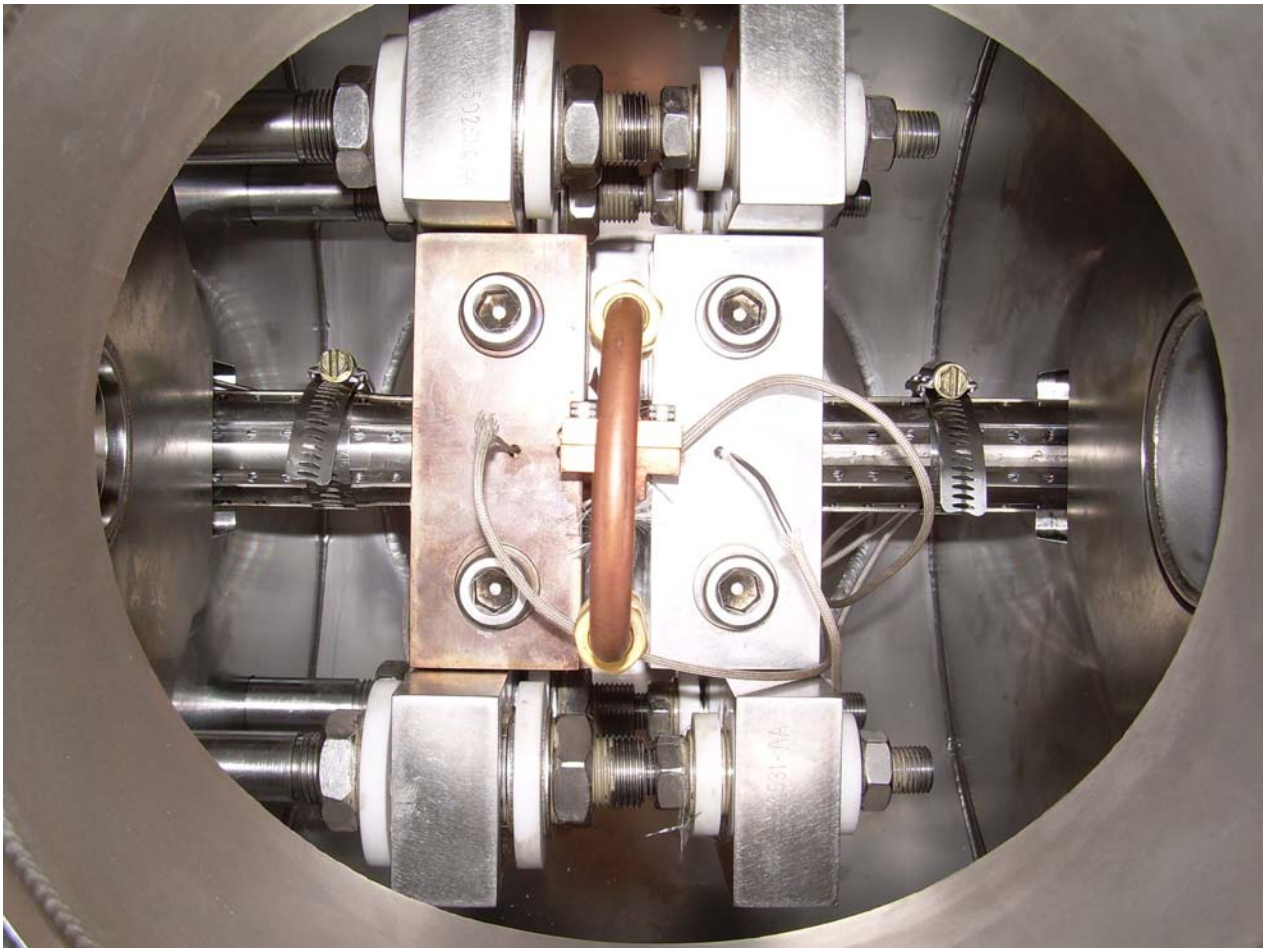


Fig. 7 view of three “central” thermocouples that were used for the process control and assessment. The band clamps on the conductors hold the thermocouples running into the jacket butts on the right and left from the joint interface. A copper jumper on the heater coil is seen connected by two steel screws. This jumper was supposed to send the current along the way of a lowest resistance, improving coupling with the joint. We removed this jumper at the later trails.

Thermocouples TC1-TC3 are seen in Fig. 7. The thermocouples assignment for this run was the following:

TC1 – control thermocouple – attached to the copper sleeve at the butt joint interface.
TC2 – thermocouple attached to the copper sleeve in the left clamp about 25 mm away from the butt joint interface.
TC3 – thermocouple attached to the copper sleeve in the right clamp, about 25 mm away from the butt joint interface.

Thermocouple TC4 was attached to the butt of the jacket from inside the vessel. This thermocouple is also touching the cable, and therefore is supposed to give us information of how hot the cable gets near the area where the seal around the conductor is made. A matter of concern is that the Viton O-ring that seals the vessel is rated to operate below 250 C. Thermocouple TC5 is attached to the opposite end of the vessel (to the right), inserted in between the butt and the cable. The remaining two thermocouples are located outside the vessel; TC6 is touching the jacket near the O-ring at the left, and TC7 is touching the jacket at the right. These thermocouples are in the vicinity of the O-rings.

Trials to develop a butt joining process of the CICC

First trials: making the power supply work

The induction power supply we used was NovaStar 5, a product of Ameritherm. This device has a self adjusting resonant frequency depending on the parameters of the working object to be heated and the induction coil. The device automatically finds the frequency that absorbs most of the energy.

First, we tried to run the induction power supply with a piece of cable crimped in the copper tube placed in the induction coil similar to what was used in the vessel. The result was not satisfactory. The induction heater power supply could not find the resonance and failed to even start heating.

We had several communications with Ameritherm who advised us on different ways to find a resonance (by narrowing the band, then changing internal inductors, etc.), but all these measures did not help.

Then an Ameritherm engineer, Dan Phelan (our principal point of contact), recommended that we rerun the device with the coil supplied by Ameritherm and used for the final inspection at Ameritherm before they sent us the device. The purpose of the rerun was to make sure that the induction power supply was operating properly, the same way as before it was sent to us. We checked this run using the configuration shown in Fig. 8 and found out that the inductive heater operated as at the factory, and the resonance frequency was as specified. That showed that the power supply was not in compliance with our load.

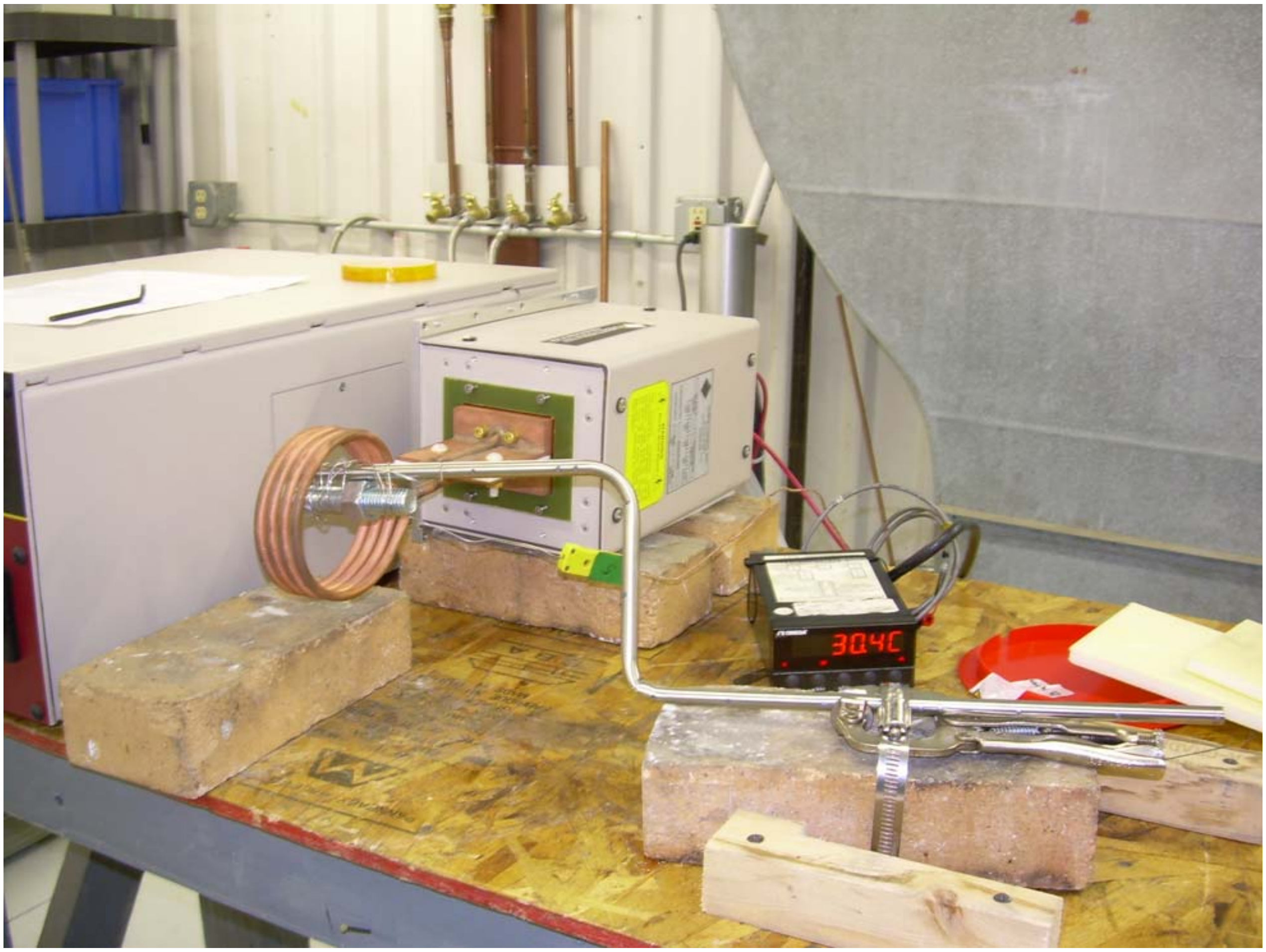


Fig. 8. A test set up with a coil sent by Ameritherm. The coil is irrelevant to our butt joint tool, but we verified that the device worked in our hands exactly as at the factory before shipping. We inserted a bolt in the bore of the coil (shown on a temporary fixture). The wire turned bright white in several seconds after we turned the device on, and the bolt started glowing red.

Thus we learned that with the existing setting of the machine, the copper sleeve and the cable do not absorb the heat effectively from the induction power supply. Therefore, something needed to be done to improve the heating efficiency. We realized that in our configuration the copper sleeves were held by the 4340 steel clamps and the clamps would absorb significant amount of power from the power supply. If they readily transfer heat to the copper sleeve, it is all we want. We set up a simple and quick arrangement as shown in Fig. 9 and reran the test.

Fig. 9. A bench test with a clamp near induction coil to check heating efficiency.

During this test, the power supply was able to find a resonance frequency at about 401 kHz, and we were able to reach about 360 C after 20 min of running. At 100% of the voltage, the current was about 22%, which is significantly lower than the optimal current in the loop (typically better than 70%). It was clear that the steel clamp receives most of the heat, not the copper. We decided to proceed with our coil inside the vessel. Although 360 C is far away from desired 750 C, we thought that: 1) the vacuum would help to reduce the heat loss, and 2) the energy deposition in the working piece would double since there would be two clamps, one on each side instead of just one as in our bench test, so may be we were already within requirements.

We assembled the piece as shown in Fig. 9 and tried to run the test. Unfortunately, the power supply could not find a resonance again. We contacted Dan Phelan again and he told us that the power supply works OK, but our coil and the working piece are outside the optimal parameters of the power supply therefore something needs to be changed. He asked us to measure the inductance of the coil, which we did and sent him the data. He said that the inductances are too small and recommended that we introduce a parasitic inductance. Marc Sipes, Ameritherm, sent a photo illustrating the idea of the parasitic inductance, Fig. 10.

Fig. 10. An example of an induction coil with a parasitic inductance.

We added an additional inductance to our circuit, just to see if it works, not necessarily to make an efficient butt joint tool. The configuration of our inductor with a parasitic inductance is shown in Fig. 11.

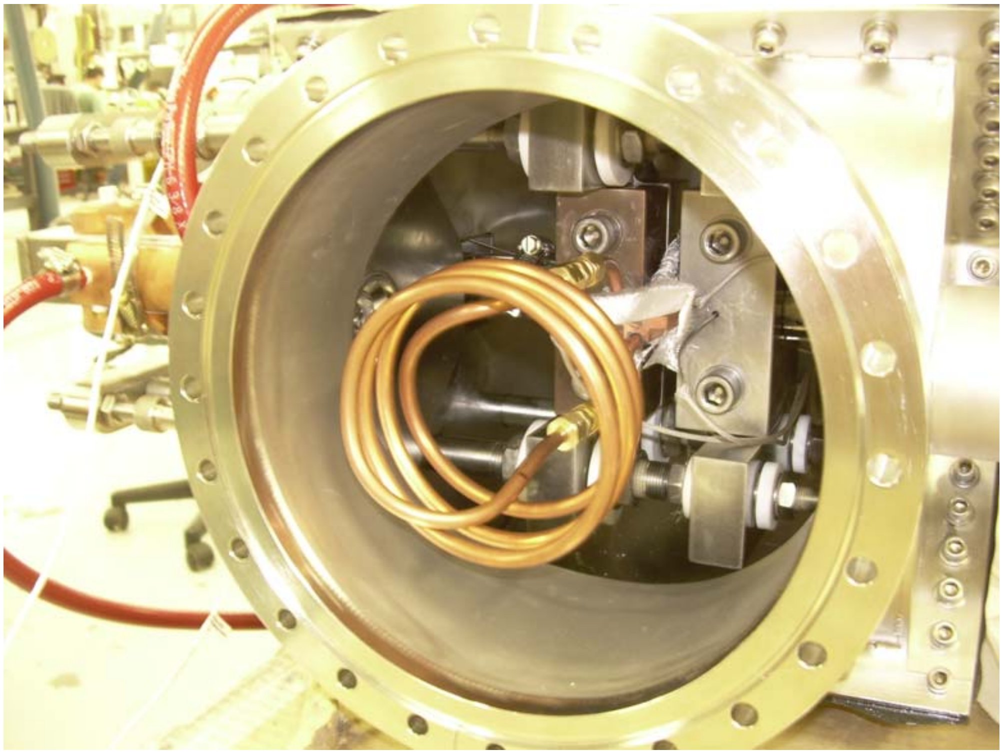


Fig. 11. A modification to the heater coil to add a parasitic inductance.

Such a configuration started working and heating the butt joint. The frequency was 163 kHz. We were able to bring the temperature on the working piece up to 520 C, but the vessel (not evacuated yet) became very hot – over 100 C, due to convection heat exchange. So, we understood that the coil like this was an effective way to find a resonance, but it was not practical to use it in the vessel in such configuration.

We modified the induction coil by eliminating the jumper between the legs of the heater coil. The jumper was intended to increase the coupling of the coil and the working piece and to reduce parasitic inductance, but it turned out that too low inductance was outside the range of automatic adjustment of the power supply. The jumper is seen in Fig. 6. We eliminated the jumper, added a loop to the induction coil to increase the parasitic inductance shown in Fig. 11. Higher inductance brought the frequency down within the adjustability range of the power supply.

We evacuated the vessel down to about 4 mtorr and attempted to heat the coil. The vacuum would not go lower, and our leak checking showed no leak at the sensitivity of 1E-8 cc*mtorr/sec. That means there must be outgassing. The suspected source of outgassing is the volatile fractions of the glass sizing, anti-galling lubricant on the threads, and molten nylon fasteners which melted when exposed to the red hot clamps and contaminated the threads of the pull rods.

It took us several trial-end-error attempts to find acceptable parameters of the power supply. We finally found a setting (450 V, 300 kHz inductor) where the power supply found a resonance and started working.

The trace of temperatures from this run is given in Fig. 12. We did not log the temperature of the vessel wall itself, but a fan blowing ambient air kept the temperature of the vessel at 62 C or below. It was too hot to touch, but not a safety concern.

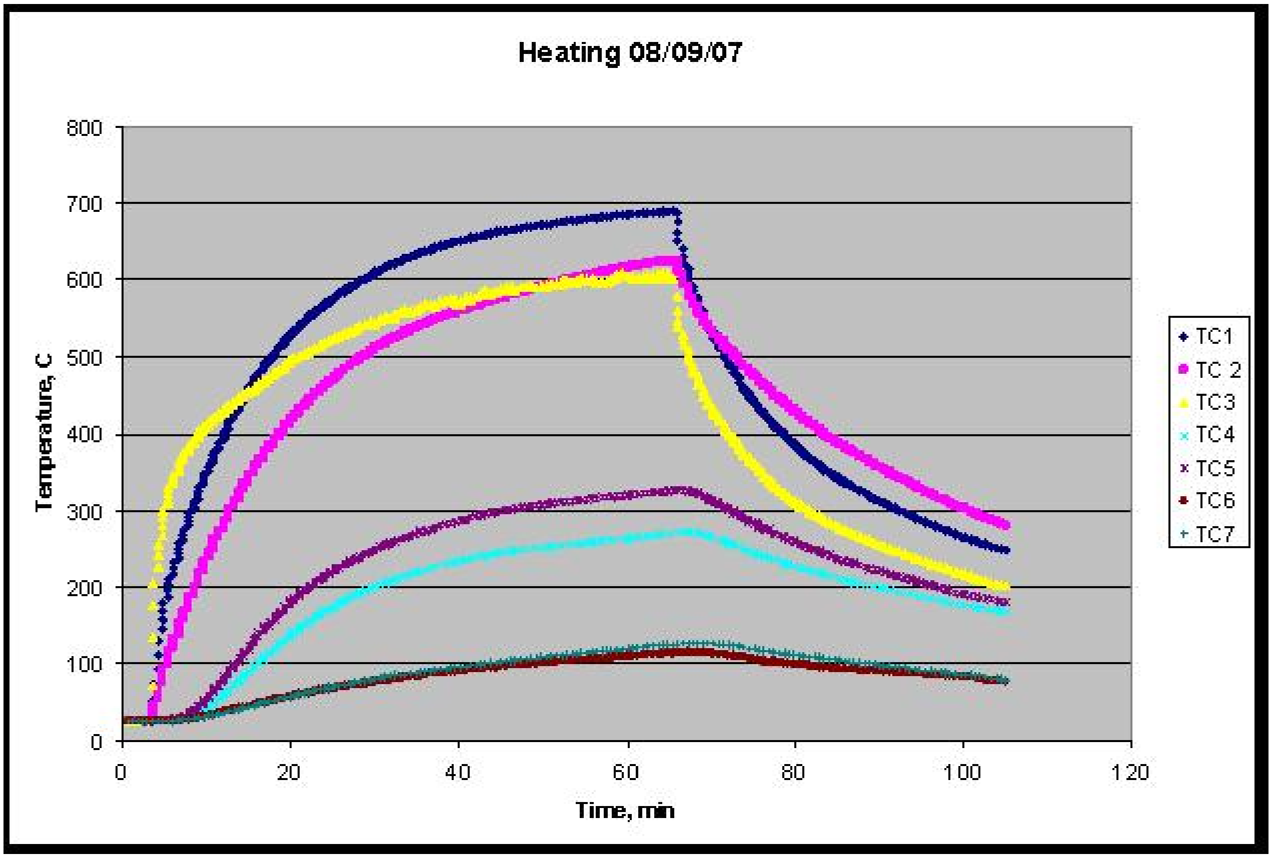


Fig. 12. Temperature traces from the 8/9/07 run.

After about 65 min elapsed time, the PS shut down due to internal interlock activation (overcurrent or overheating). The overheating for the water is usually set about 90-95 C, according to Ameritherm engineers. We checked the temperature of the cooling water by touch and it was not particularly hot, so we assumed that the interlock activated due to overcurrent in the PS. The frequency of the circuit was 296 kHz and the current at 100% voltage was 61-62%. , According to Ameritherm, this is less than optimal but much better than in the previous runs.

A significant fraction of the heat came from the clamps. Despite the poor quality, the picture in Fig. 13 (taken from the outside the vessel viewport) shows a glow coming from the clamps, particularly from the right one, and not much from the working piece.

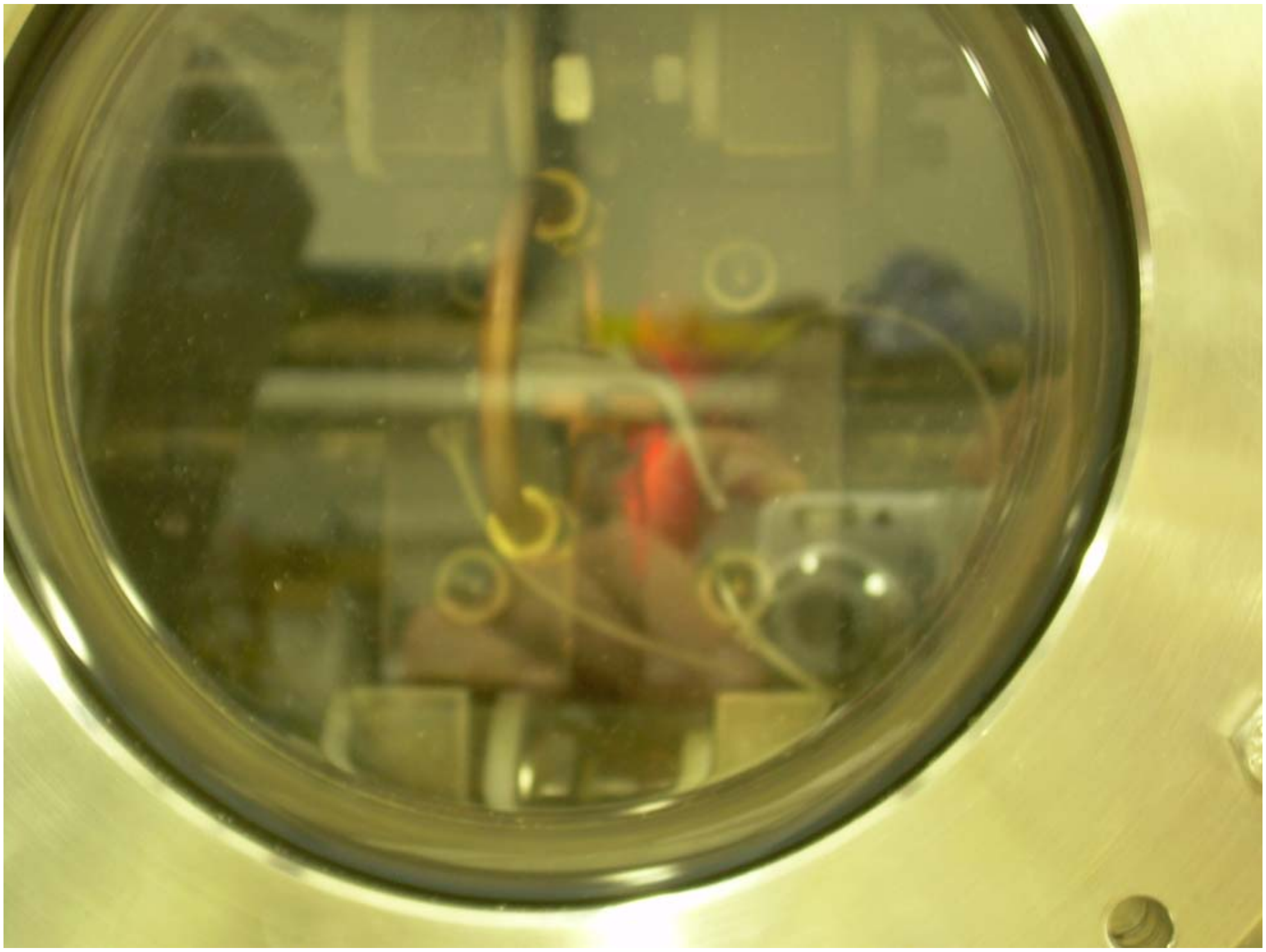


Fig. 13. Butt joint tool during the 08/09/07 run. The glow comes mostly from the clamps.

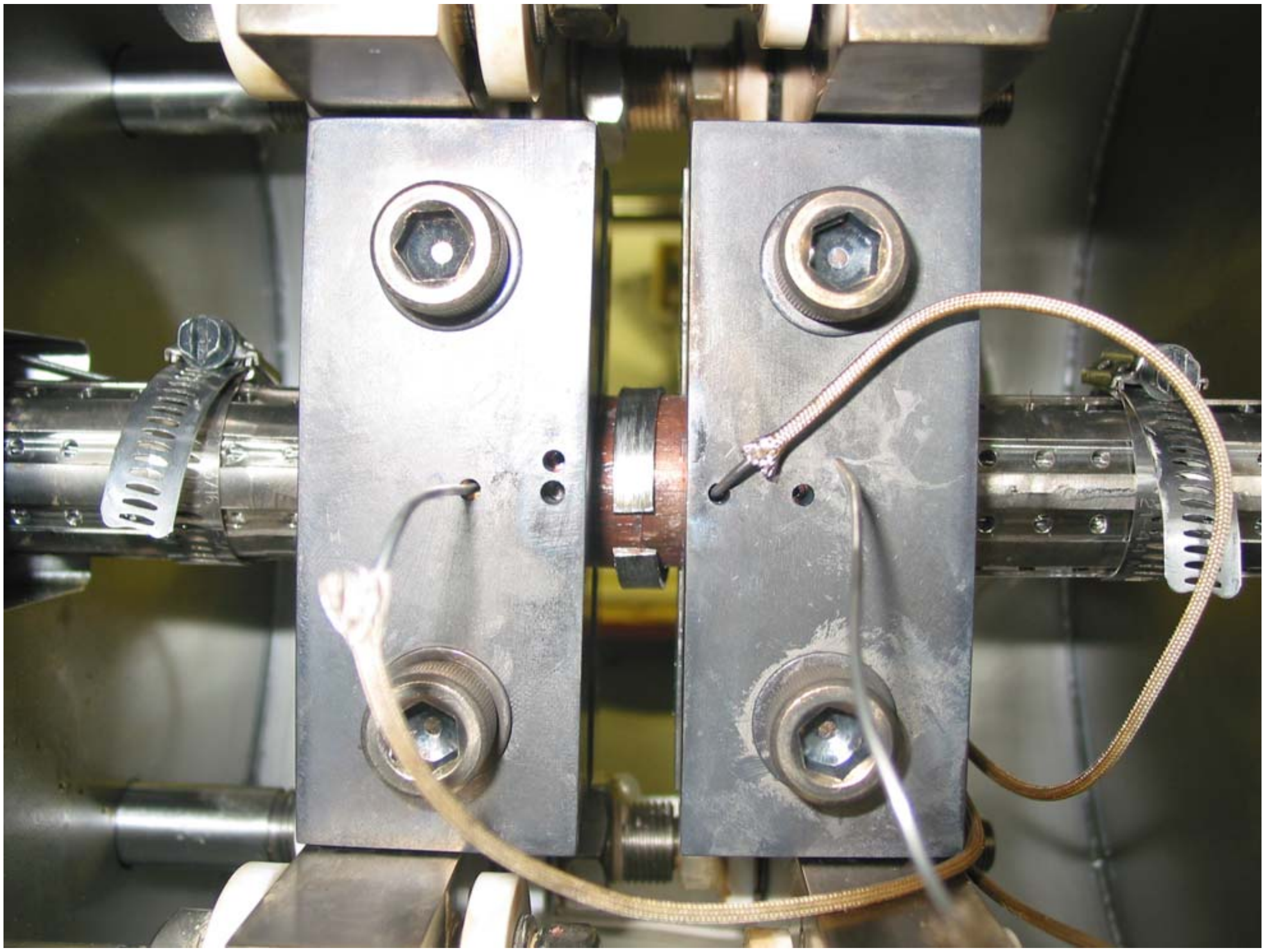
Conclusions from this run are:

1. We approached the desired temperatures of 750 C, but the rate was too slow, and we did not quite reach 750 C. We needed to improve power transfer from inductive power supply to the working piece. In this configuration, the power supply could not handle 70 minutes of heating (trying to reach the desired temperature) and overloaded itself.

2. Other systems functioned well. One of the concerns we had was that the areas where the O-rings are sealing the conductor would be too hot and the Viton would not hold the vacuum. We kept the heating on for 70 min, which is representative to the real cycle. The temperature from inside the vacuum on the butt of the jacket is a little scary – exceeds 300 C. So, the O-ring temperature is somewhere in between that and the thermocouples inserted from the outside, showing temperature below 120 C, which is comfortably low.

Trying to improve heating efficiency: using steel hot rings

To improve the heating efficiency, we installed a thin steel ring (about 10 mm wide, 2 mm thick) held by a band clamp. Let us call this configuration “hot ring 1”, since we modified this concept later. The idea behind this approach was that the steel ring would absorb more energy, get hotter, and help to bring the butt joint interface to the desired temperature by optimizing the PS and providing additional heating from the steel ring. The steel ring was not continuous; it had a 2-3 mm gap. The thermocouple was mounted touching the copper sleeve in this gap as shown in Fig. 14. The two photos in Fig. 14 show the configuration before and after installation of the band clamp and the control thermocouple. The other thermocouples were installed as specified before.



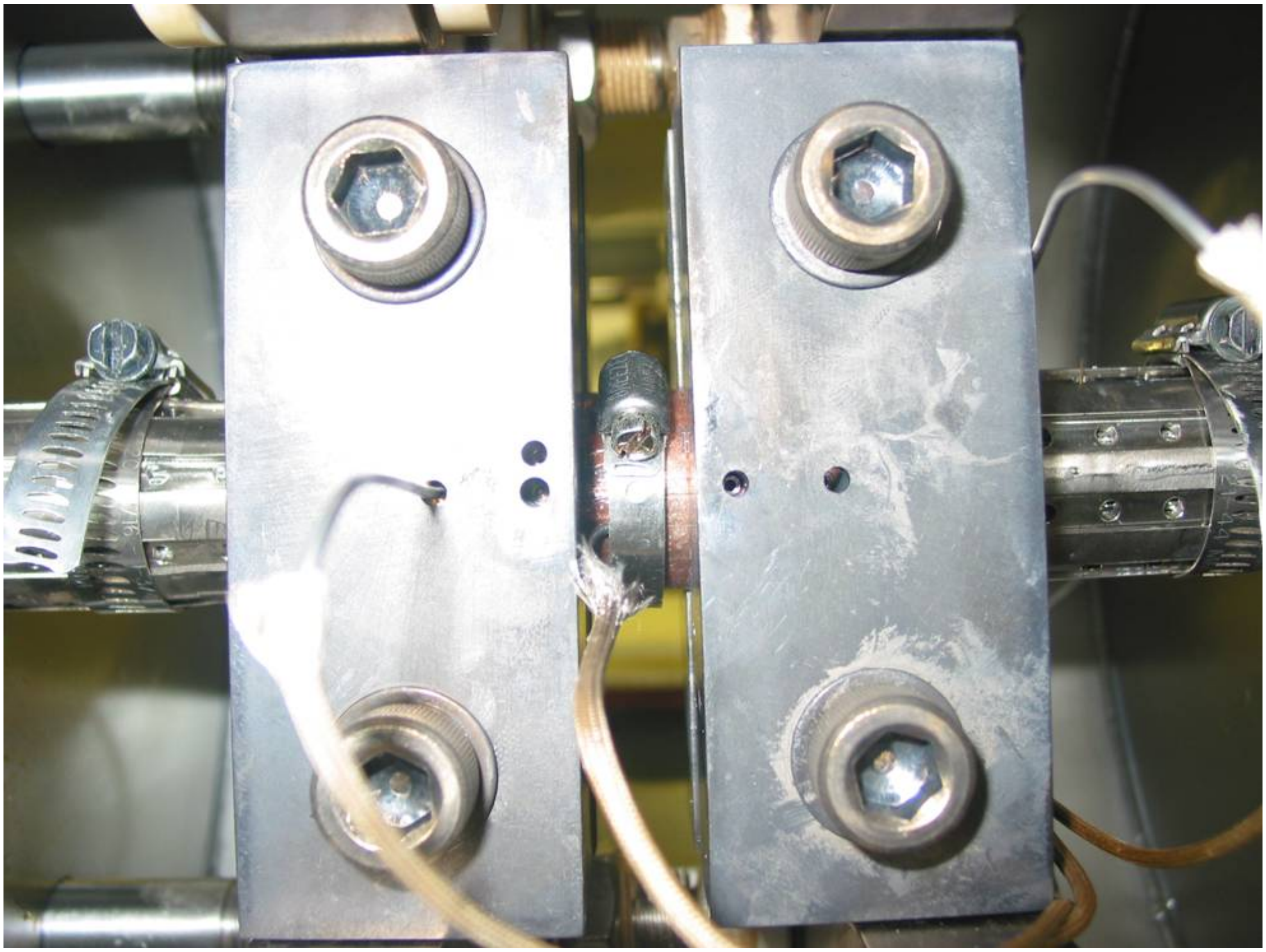


Fig. 14. Hot ring 1 configuration. The SS ring is installed underneath the band clamp in the middle, shown on the top photo without the band clamp. Photo below shows the assembly with thermocouple attached to the copper sleeve in the split of the hot ring.

The results of this run are shown in Fig. 15. Again, after 75 min, the interlock activated due to the current exceeding the allowed limit and shut down the power supply.

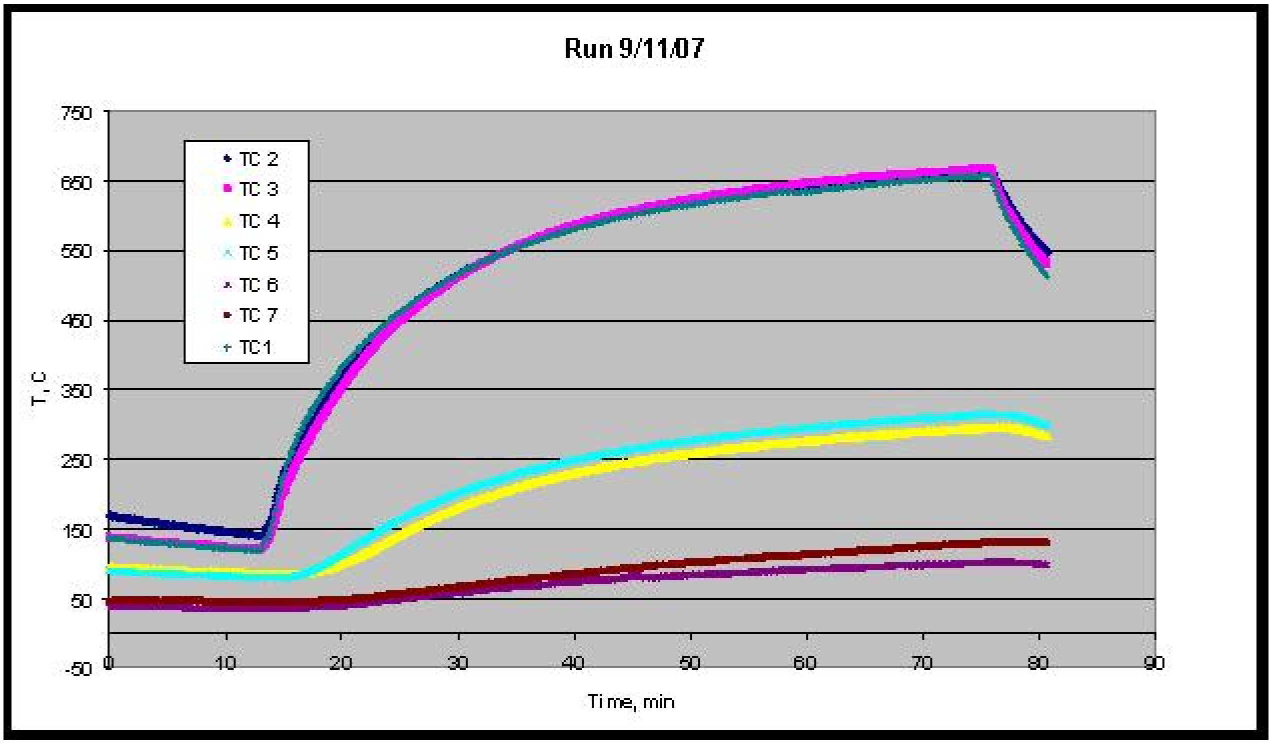


Fig. 15. Temperature traces for the 9/11 run.

Comparing these results with what we achieved on 8/9/07 (see Fig. 12), we see insignificant improvement in time, and the temperature between the interface and the sleeve under the steel clamp was much more uniform than on 08/09, where this distance was 25 mm. Fig. 14 (top) shows that the right thermocouple, TC3, was not 25 mm away from the interface, but rather 13 mm away. I am suspicious that for the particular ran on Fig.15, the left thermocouple was also 13 mm away, not 25 mm as Fig. 14 suggests.

The frequency of the PS for this run was about 300 kHz, similar to the 8/9 run; the current at 100% voltage was 59% versus 62% for the 8/9 run. This slight differences occurred because between 8/9 and 9/11, we changed configuration of the heater coil a little bit. It was due the fact that we experienced a problem with the water fittings. To save time, we bought the 0.25" pipe and pressure fittings (Swagelok type) from Home Depot, instead of from a more reputable supplier. We discovered that under vacuum these fittings leak in 2 cases out of 3, and tightening the nuts did not help. While waiting for delivery of higher quality parts, we used the usual plumbers soldering technique, which turned out to be much easier and more reliable. Connections made by Steve Kenney never leaked and were quicker and easier to make than to tighten in a constrained space of the vessel.

So, adding the hot ring 1 did not lead to better results. We saw much higher glow at the interface where the hot ring was, and not at the clamps as much as before, which is positive, but we could not reach specified parameters.

Changing the capacitors bank in the induction heating power supply

Failing to reach 750 C, we consulted Ameritherm again and their application leader Dr. Girish Dahake recommended using a different set of capacitors to shift the frequency to a lower level. He sent us the capacitors, and we installed them on 9/20/07.

We changed the capacitors and ran the butt joint tool again, still with the hot ring. Before we did a qualification run, we varied parameters of the PS (inductors) to see if the performance of the PS would vary and found that it was not affected by much.

The frequency of the PS was 215 kHz and 200 kHz inductor setting was a little better than 150 or 250 kHz. Increasing of the voltage from 300 to 375 V did not help either. The results are shown in Fig. 16. So, the optimum is somewhere around 300 V and 200 kHz. The current at 100% voltage was at the level of 72%, and at 375 V and 150 kHz it was 55% or so. That shows that the optimum operation is quite sensitive to the settings. But the improvement was obvious; we could reach almost 700 C in 15 minutes or faster.

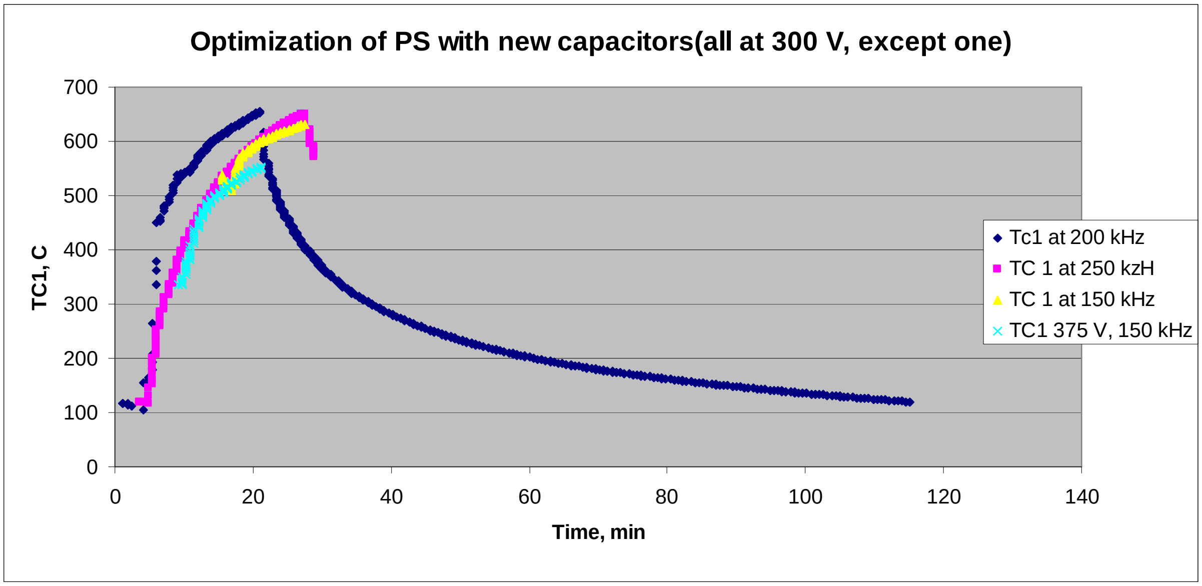


Fig. 16. Optimization of the PS with new capacitors and the steel hot ring 1.

By 9/21 we also modified the hot ring as shown in Fig. 17, not only to provide additional heating from the hot ring, but also to hold the thermocouple contact to the copper sleeve in a more reliable way. As one can see, the thermocouple protrudes through the ring, which has a groove. This groove assures that the measurement reads the temperature of the sleeve, not the steel of the ring. The thermocouple does not have a reliable thermal contact with the ring up until the entrance at the ferrule of the Swagelok, 25-30 mm away from the copper sleeve. Hot ring 2 was made of low carbon magnetic steel to increase the efficiency, not only by higher resistance, but also by losses due to magnetization.

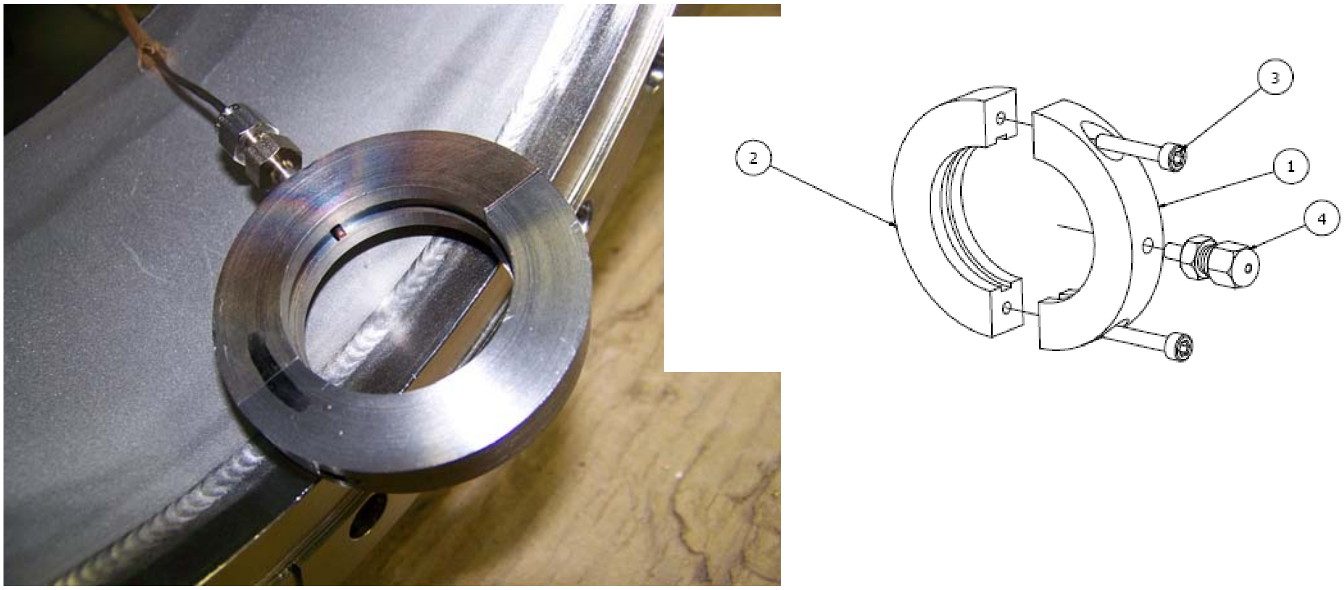


Fig. 17. Hot ring 2 with the thermocouple, photo and exploded view.

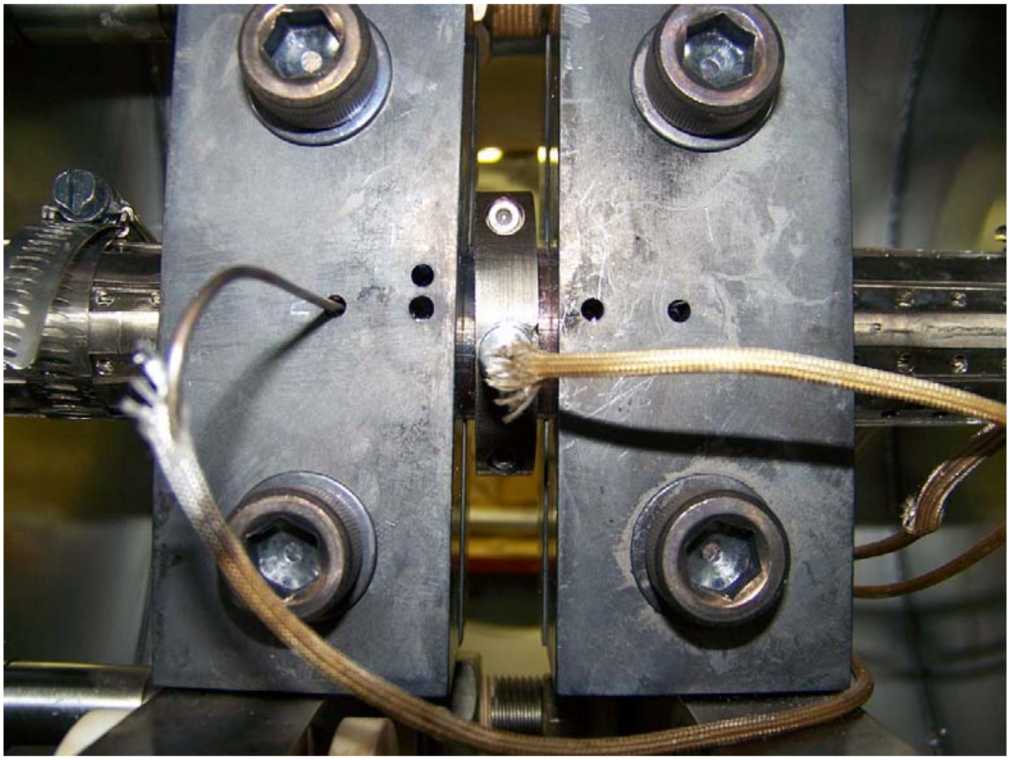


Fig. 18 shows the installed thermocouple. inside the vacuum vessel.

Fig. 18. Hot ring 2 with a thermocouple installed on the butt joint interface.

This run took place on the 9/21/07 and showed that indeed the temperature of the butt joint sleeve went up to the desired level very fast. The current at 100% of the voltage was at 72-74 %, which is in the ball park of what Ameritherm told us the optimum should be. After reaching the controlled temperature on the surface of the sleeve 750 C, the power regulated correspondingly. The temperature traces are shown in Fig. 19.

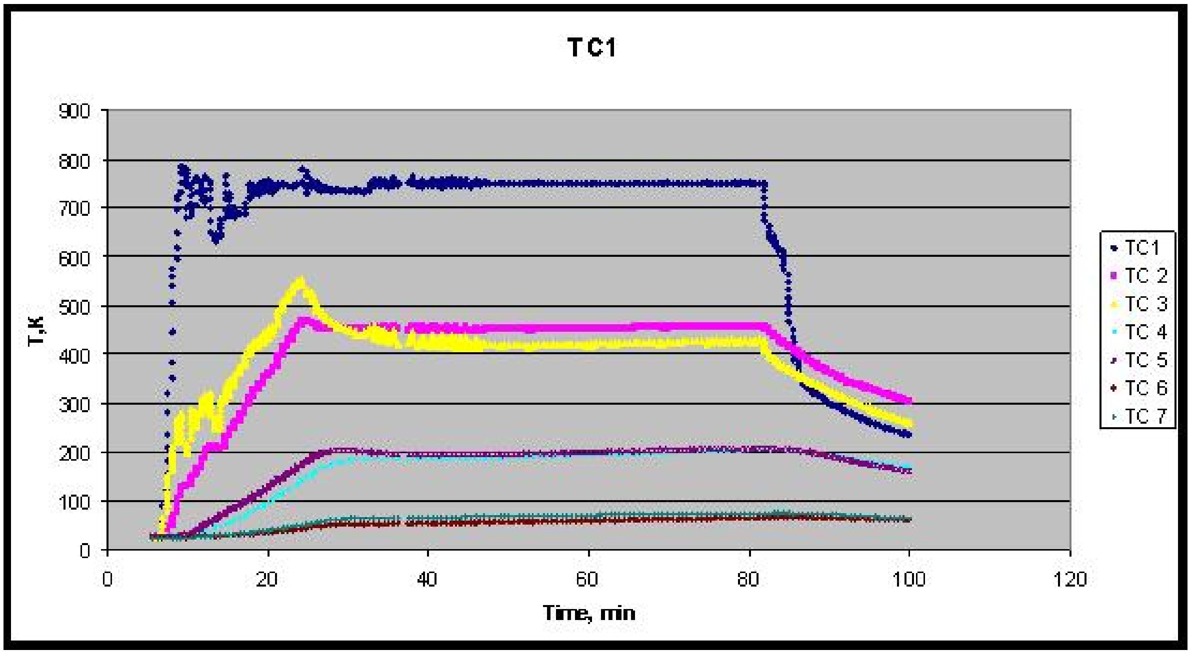


Fig. 19. Temperature traces with the “hot ring 1” installed Sept 21, 2007.

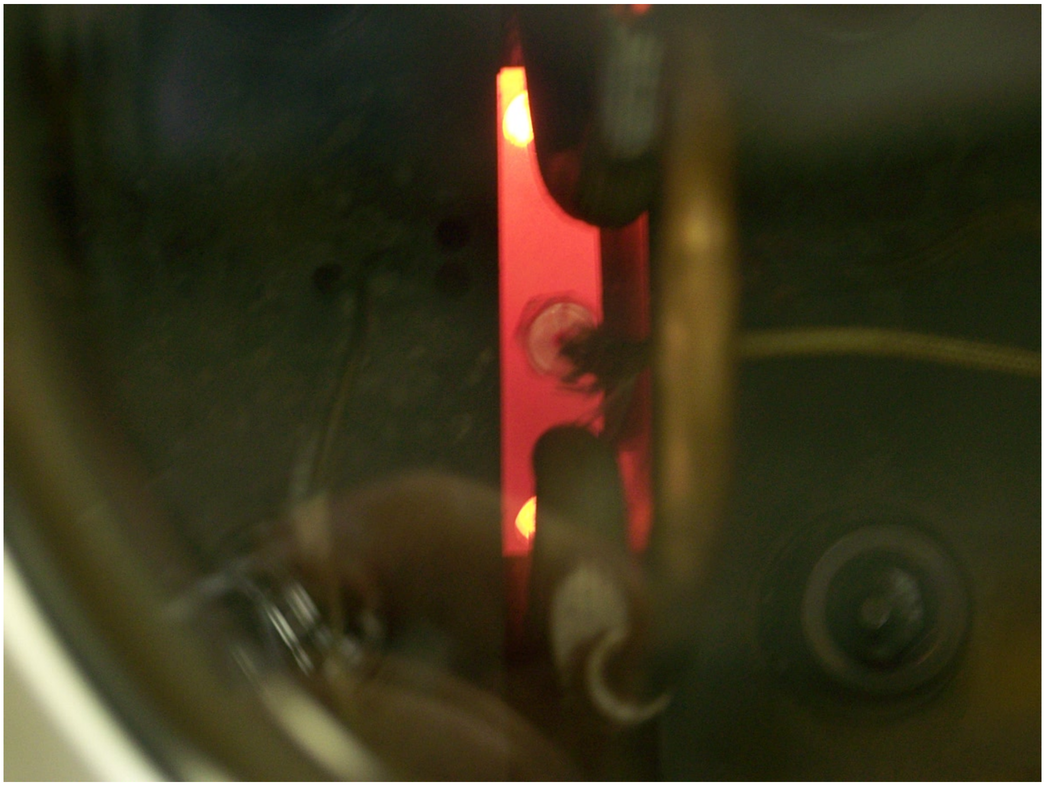


Fig. 20. Hot ring 2 in action. One can see that the fasteners holding the hot ring together are white hot, an indication of much higher temperature there. This is not surprising since

all the circulating current has to pass through a much smaller cross sectionof the bolt, much smaller than the ring.

Formally, we accomplished the most important requirement for the butt joint of holding the butt joint temperature at 750 C for over 70 minutes at a vacuum of about 10 mtorr and at 2 t load. The hot ring was glowing red hot, shown in Fig. 20.

However, on the second thought and after simple analysis, however there are some worrisome things. First of all, it is not possible to miss, that the temperature of the clamps is about 450-470 C. Only 20-25 mm away from the point at 750 C! Let’s see if energy conservation law holds. Let’s assume that the copper thermal conductivity is 400 W/mK. Let’s also assume that the temperature distribution is uniform in the cross section and see how much power we need to supply to explain such a major temperature gradient. We use formula:

$$W = 2\lambda \frac{dT}{dx} S$$

Plugging the numbers we arrive at 9 kW. We know that maximum power of the Nova Star is slightly over 5 kW at 100% voltage and current (according to Ameritherm).

lambda	400	W/mK
Cross sect	0.000755	m2
Length	2.00E-02	m
dT	300	K
W	9.06E+03	W

At 70% current and 100% voltage, we provide 3.5 kW to the coil, of which most, but not all power goes to our butt joint. So the power balance is off almost by a factor of 3. There is not much uncertainty in the parameters, so the only explanation is that the temperature profile across the cross section is not uniform. So, it looked like we heated up the butt joint very locally, right near the interface, due to very high temperature of the hot ring, but the total amount of heat entering the butt joint was lower than even in the previous runs. See for comparison, Fig. 11, showing the run on 8/9/07 to see that the temperature of the sleeve 20-25 mm away from the interface is only 50-80 C away and closing, which makes much better sense. So, clearly the hot ring does bring the temperature on the surface of the interface to 750 C very quickly, but there is a reason to suspect that inside the joint, it is much colder.

I discussed this matter with Y. Takahashi-san, who was the project engineer of the butt joint development for the JA Outer Module for the CSMC. He said that the 750 C temperature was measured on the clamps of the butt joint in production of the Outer module.

The configuration of their temperature sensors was as shown in Fig. 21. As one can see, the tips of the thermocouples are attached to the structure close to the copper sleeves, not to the copper itself.

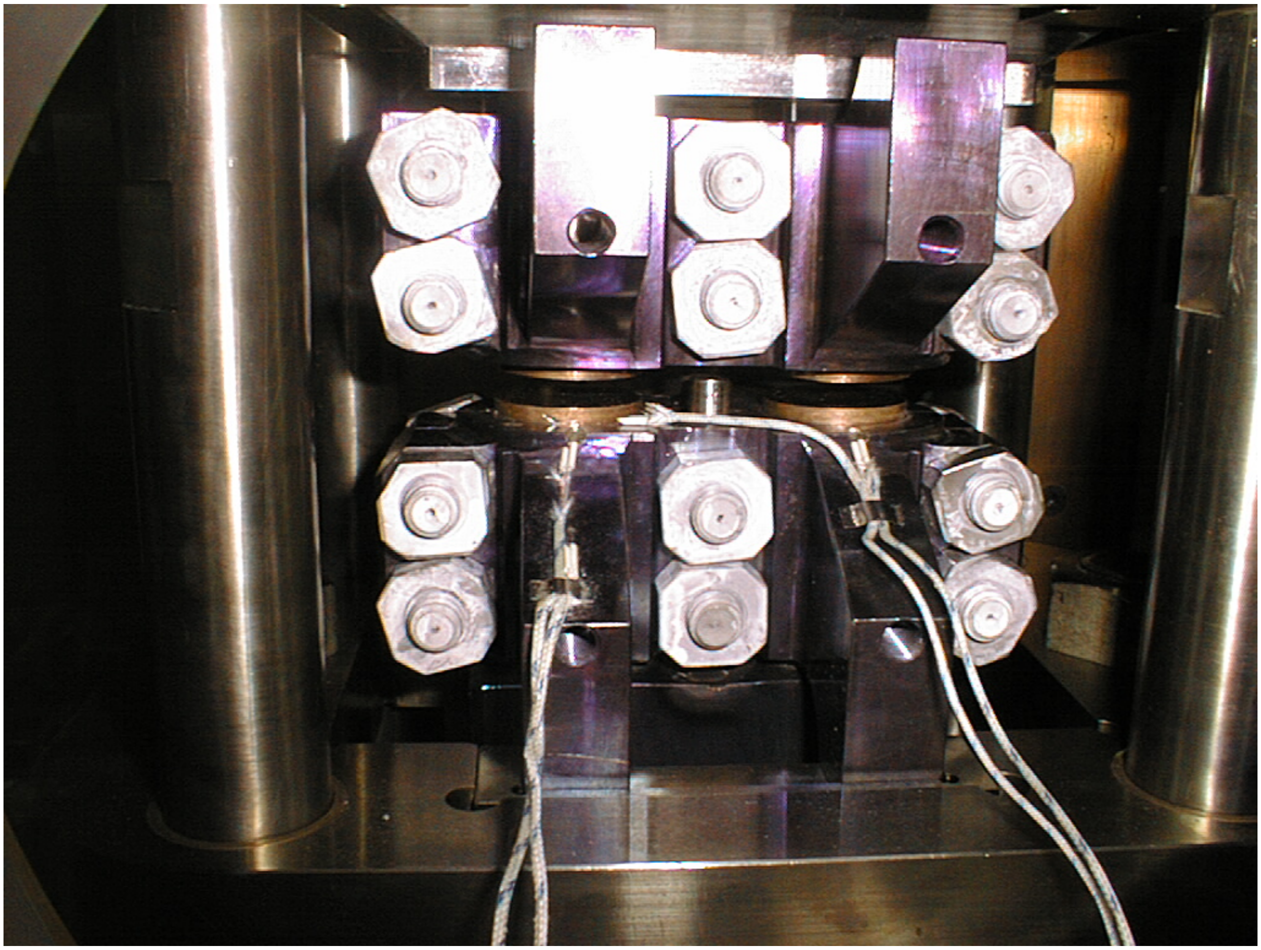


Fig. 21. JA configuration of the temperature measurement in the production. (Courtesy of Y. Takahashi)

At the R&D phase, the JA team measured the temperature of the sleeves as well as the thermocouples on the structure, shown in Fig. 21. They discovered, according to Y. Takahashi (private communication), that the surface of the sleeve becomes 680 C when the clamps are at 750 C. According to their analysis, the temperature of the center of the interface is 650 C after 0.5 hour of holding time. But they did not verify it with measurements to my knowledge.

In any event, our measurements are not consistent with the assumption that the temperature in the cross section is uniform and we decided to explore that in more details. For that we needed to remove the hot ring 2 and drill a hole in the sleeve to plant the thermocouple right in the middle of the crimped cable.

We discovered that the machine screws were soft and galled, so the only way to remove them was to drill them out. Also, the thermocouple got sintered to the hot ring, which suggested that the temperature of the ring was much higher than 700-800 C.

We decided to machine a new ring, same geometry, but use titanium screws. Titanium has much higher melting point and presumably would not get affected by high temperatures.

While machining was going on we decided to drill a hole in the sleeve with the crimped cable and install a thermocouple inside it to measure directly the temperature inside. For this purpose we re-used the hot ring 2, but instead of machine screws we used a welding rod 1/8” as tie wire through the holes.

When we started running this test we reached 700 C on the thermocouple attached to the sleeve surface. The thermocouple installed inside the sleeve burned out.

After opening the vessel we discovered that the welding rods serving as a fastener burned out as well.

That indicated that the hot ring fasteners heat up to the level of above 1500 C. That gave a basis for speculation that when we measured 750 C on the surface of the sleeve on 9/21 (see Fig.19) the thermocouple possibly measured some intermediate temperature between the surface of the sleeve and the hot ring which was possibly at much higher temperature than the butt joint. We did not have extra thermocouples to find out how hot the ring goes.

Our next trial was with Ti screws and a new hot ring 2, with the same design as before. The temperature traces are shown in Fig. 22.

Since we lost some thermocouples, we ordered new thermocouples with a high temperature sheath, but decided to proceed with limited number of thermocouples. We rearranged the thermocouples in the vessel.

The thermocouple 2 was inside the middle of the butt joint, about 13-15 mm deep. The TC1 was the thermocouple on the copper sleeve surface and TC1 was the control thermocouple, as usual. The thermocouple inside the sleeve was TC4. The TC2 was the thermocouple touching the sleeve 25 mm away from the joint, routed through the left block and TC5 is the thermocouple touching copper sleeve 20-25 mm away from the joint routed through the right block.

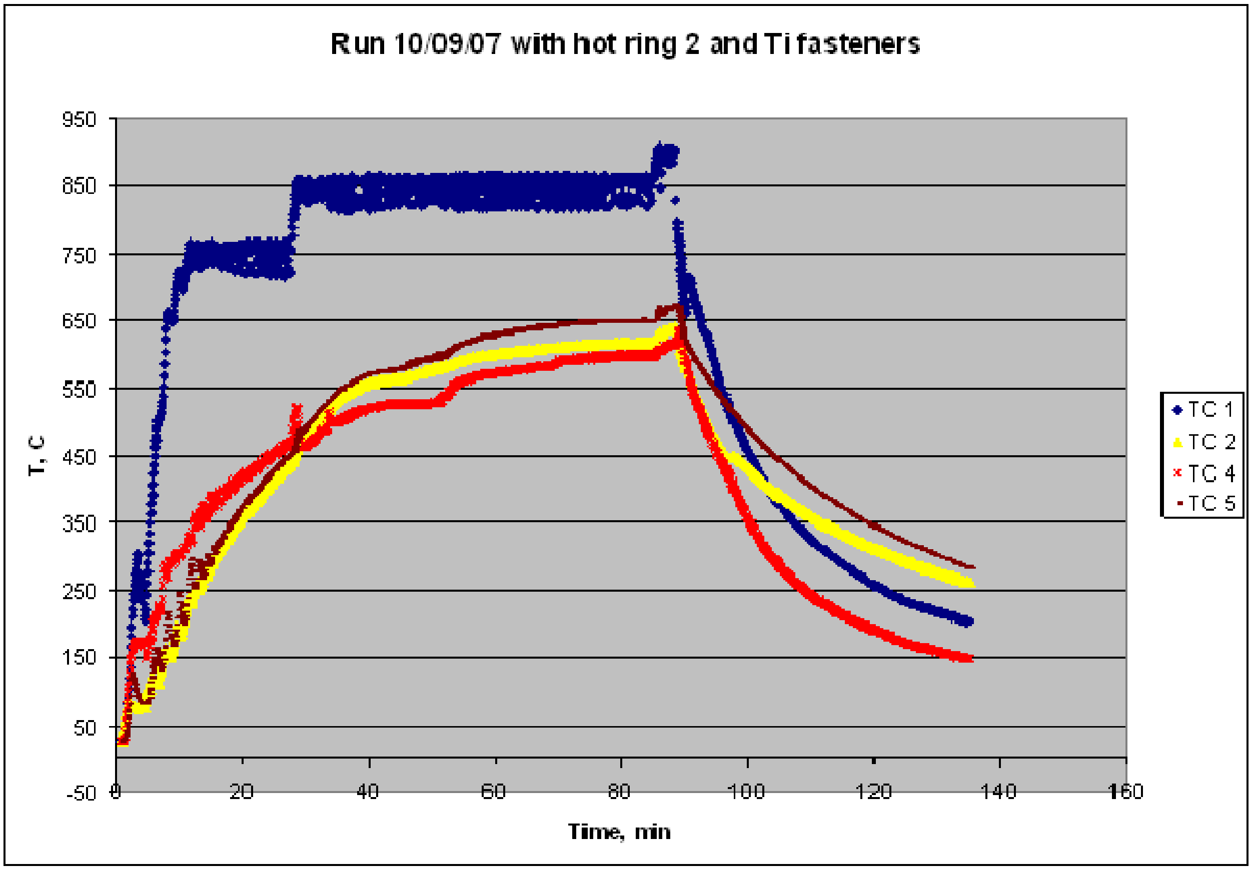


Fig. 22. A successful run with hot ring 2.

As we can see, the surface of the sleeve gets hot from the hot ring very fast, which is a good improvement. But the temperature inside the sleeve would not go above 480 C in 30 min of “cooking” because the power supply is programmed to maintain the temperature on the surface at whatever we ask (750 C in this case) for the first 30 min. We could see that it took very little energy to maintain 750 C at the surface, and the power supply was constantly turning on and off. That means that the all power was going to the hot ring and not much into the cable. After 30 min we dialed 850 C on the surface, and we got it, but the temperature inside the cable rose to only 600 C after 85 minutes of “cooking”. That suggests that there is a very powerful heat removal along the cable and relatively weak conductance across the cable. This was unexpected; we did not expect that the temperature gradient across the tightly compacted cable could be that high.

When we get to the temperature on the copper surface of 900 C, the temperature inside the copper sleeve went up to 626 C, but it was uncomfortable to go that high in the joint.

We can also see from Fig. 22 that when the power was turned off, the temperature inside copper sleeve dropped faster than outside. This was very much unexpected. Again the only rational explanation to that is that the longitudinal thermal conductivity is much greater than the transverse conductivity. So while the surface has a large hot mass attached to it (the clamps), the inner part of the cable just gives away heat through the longitudinal conductance and cools off faster than the sleeve surface where cooling is slowed down by large amount of heat stored by the clamps.

So, with the new capacitors and the hot rings we had a much better success in generating higher temperatures on the butt joint surface. But penetration of heat inside the compacted cable was not very good. We had no problem to maintain the target temperature of 750 C on the surface, but temperature inside the compacted cable was much lower and made us wonder if it would give us a high quality joint. If we have a defect, it will be like a built-in crack that may not have a good cyclic life.

Running the tool without hot ring with a new capacitors bank

Obviously, we did not run this test first because the logic of our results led us in a different direction, that hot rings are useful. After we saw that the hot rings indeed help bringing the surface temperature to 750 C in minutes, but left the cable inside not that hot, we decided to run an experiment without any hot rings hoping that the heat generation will penetrate deeper and will have a volumetric nature, rather than coming from the surface. That would make a temperature distribution more uniform in the cross section. Thus, we made a full revolution in our development. First we introduced the hot ring to increase efficiency, then we abandoned it hoping to increase efficiency more. It happens in developments like this. In between we changed the capacitors, of course and that seemed to be the major difference.

The configuration we tried is shown in Fig. 23. It shows no hot rings and all 5 thermocouples inside the vessel active.

The positions of the thermocouples were as follows:

TC1 - touching copper on the surface at the interface
TC2 is inside the copper 12-15mm deep at the interface
TC3 is in the left clamp touching copper, 13 mm away from the interface
TC4 is in the right clamp, touching copper 13 mm away from the interface
TC5 is at the right flange (conductor entering vessel) from inside
TC6 - on left, outside vessel near Oring
TC7 - on right, outside vessel, near Oring

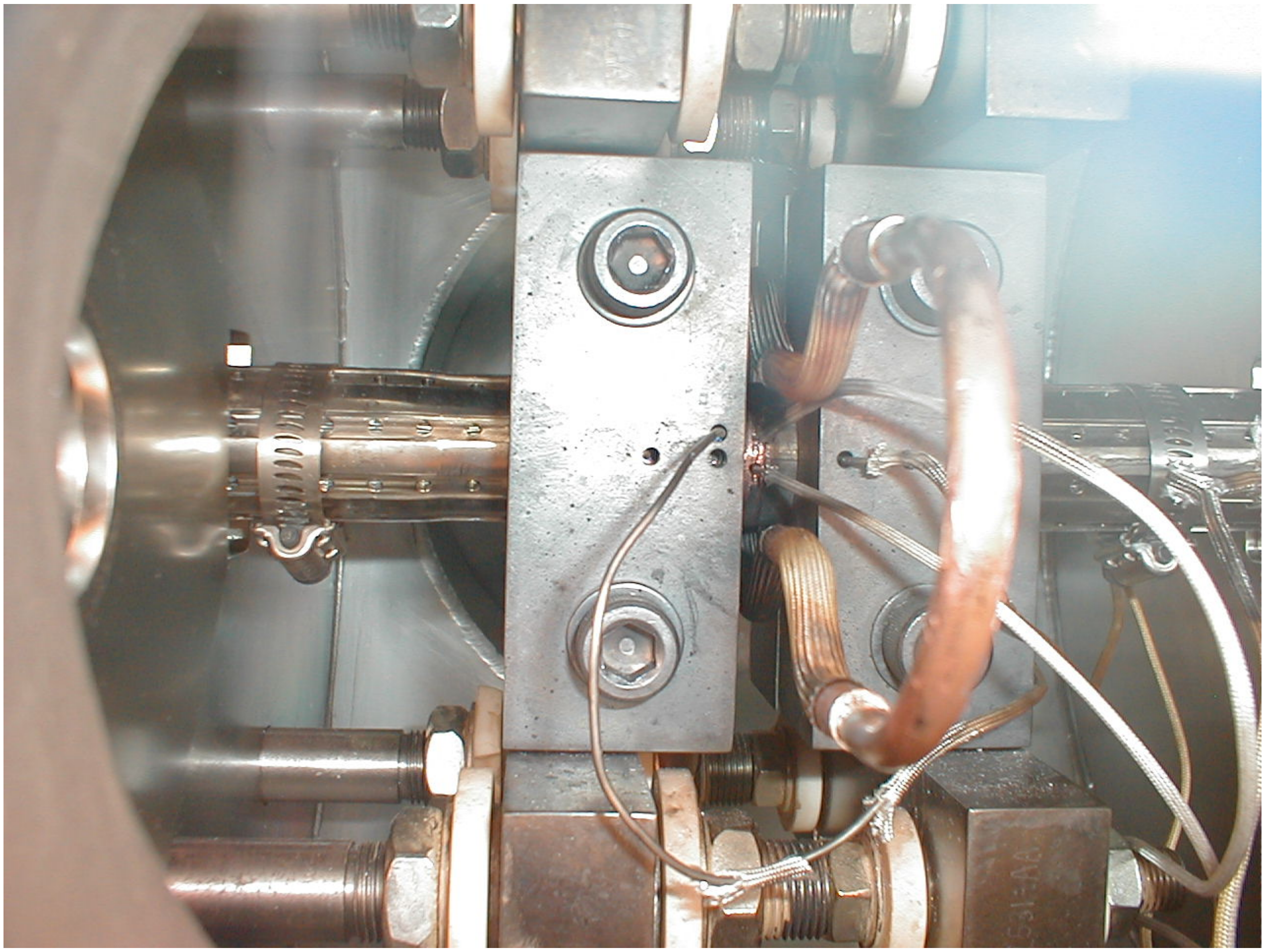


Fig. 23. Arrangement of the thermocouples without the hot ring but after capacitors change.

Fig. 24 shows the temperature traces of the sensors during the run on 10/11.

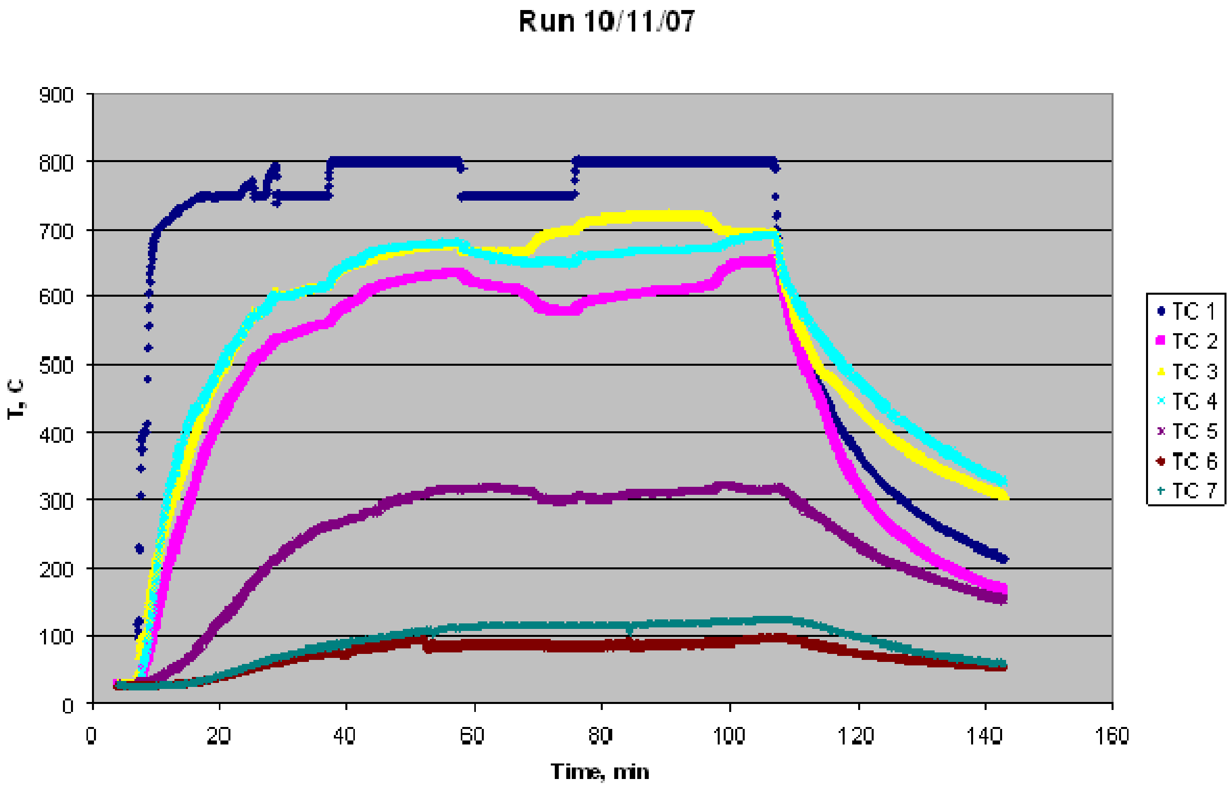


Fig. 24. Butt joint bonding run on 10/11.

As one can see that with the new capacitors we reached the temperature of the sleeve 750 C acceptably quick – in about 10 minutes. But the temperature inside the cable was low, although about 100 C higher than in the previous run with the hot ring. In about 33 minutes (40 min on the time axis) after we turned the heater on the temperature inside the joint reached 570 C. At this moment we decided to see if we can accelerate the heating inside and dialed the control thermocouple to 800 C. We did it since we saw that the system is close to equilibrium and that the temperature inside the cable TC2 would not go much higher than 570 C. We verified that later (that it would not go much higher than 570 C indeed) in the period between 60 min and 80 min on the time axis, when we lowered the TC1 setting to 750 C. After waiting 20 min, TC2 value stabilized at 577 K. Thus, if specify 750 C on the surface for 70 min, we have the middle of the joint at 577 C for about 40 minutes, since it takes about 30 min to get to 570 C.

Our JA colleagues convinced themselves by analysis that while the temperature on the surface is about 680 C, it is 650 C inside. We measured that it was much lower. There are at least two possibilities:

1) The temperature in JA trails was about as low as in our case. They just did not know that, since they did not measure it. However the butt joint performance came out OK in the CSMC. That means that may be 570 C is sufficient for good resistance and may be

for structural strength as well (or even lower temperature in JA case, since their temperature on the copper sleeve surface was 680 C according to Takahashi-san, private communication) as opposed to our 750 C or higher. Thus, we just control the surface temperature on the copper sleeve 13 mm away, in the clamp to 750 C for 70 min.

2) Our way of cooling the conductor coming out from the vacuum vessel is possibly much more intense than in the JA apparatus (my unqualified speculation). The vicinity of the heat intercept generates a high nonuniformity in our case and may be not so much in the JA apparatus. In our case the cooling of the jacket is only about 160 mm away from the interface with the water cooled blocks. We can not avoid cooling of the conductor due to risk to burn Viton O-rings (good to 250 C). Possibly, in JA apparatus the cooling is much farther away, which may result in a more uniform temperature distribution.

At the moment we tend to accept speculation No. 1, and we proceed with this scenario. We will investigate the structural and electrical performances and will come with a conclusion if this procedure is adequate for the successful operation.

Possible improvement may be to increase the thickness of the copper washer from say 0.1 mm to 1 mm to provide a reliable path for heat to go inside. A 1 mm thick washer with RRR=100 will give additional 0.26 nOhm in resistance. With the requirements of the joint resistance to be less than 5 nOhm, it may be acceptable.

As before, Fig. 24 shows that the temperature inside the copper cable drops faster than at the surface. That indicates again, that the cooling from the surface is slowed down by the large mass of the hot clamps attached close to the surface, while axial heat removal is intense which makes it possible that the cable core becomes cooler than the surface.

Conclusion

After small modifications to the original butt joint device, the system now operates reliably and in a well controlled manner. All subsystems operate successfully. We identified small improvements to make the operation more convenient. We will start making samples for structural integrity (strength) testing, and after that we will make samples for joint performance testing (electrical resistance, dependence on current and temperature).

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