# NEW DESIGN FOR THE MKI RF FINGER CONTACTS IN THE LHC

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### *Abstract*

The radio frequency (RF) finger contacts for the injector kicker magnets (MKI) that inject the beam from the SPS to the LHC at CERN must be re-designed. This part must satisfy several stringent requirements in terms of temperature resistance, mechanical robustness, electrical contact resistance, and vacuum requirements. The current design does not consistently meet these standards. An analysis of the current design will be presented as well as suggestions for an improved design.

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## 1. Introduction

The Large Hadron Collider (LHC) being constructed by the European Laboratory for Particle Physics (CERN) will collide counter rotating proton beams for collisions with energy on the order of 14 TeV.[1] The Injection Kicker Magnets (MKI) are responsible for transferring the beam from the Super Proton Synchrotron (SPS) to the LHC. Within these magnets, there must be a flexible electrical contact between the end of the ceramic beam pipe and the next section of the beam pipe. This connection must have low electrical resistance in order to obtain a low beam impedance. As well, the connection must result in low RF losses to the surrounding tank cavity. Finally, the connection must accommodate potential errors in the assembly of the magnet. Failure of the RF contact fingers would increase beam impedance to high enough levels that would cause the Ferrite magnet to go above its Curie temperature. This could cause the kicker magnets to fail to deflect the beam. The current design does not consistently meet these stringent demands and a new design should be created before the LHC becomes active.

## 2. Requirements

### *Bake-Out*

The RF contact fingers must maintain their mechanical properties after a harsh bake-out process. More specifically, the entire magnet is initially baked out to 300$^0$C for approximately 100 hours for vacuum reasons.

The extremely high temperature and long bake-out process causes thermal expansion to occur in the magnet. Both the expansions of the tank and the beam tube need to be taken into account, and where each object is fixed also has an effect. The tank is is made out of AISI 304L Stainless Steel which has a coefficient of thermal expansion of 17.3 μm/(m·K).[2] It is fixed in the center of the magnet, so its expansions will be calculated from that point. The ceramic beam tube is made out of Alumina 99.7% $Al_2O_3$ which is fixed at the right side of the magnet.[3] This material has a thermal expansion coefficient of 7.5 μm/(m·K).[4] This causes the difference in expansion of the fingers and the tank (effectively how much the fingers will slide) to be broken into three parts. Assuming a constant bake out temperature of 300$^0$C, and room temperature of 20$^0$C the calculation becomes[5]:

$$\Delta L = 280^0\,C(17.3*10^{-6}\frac{\mu m}{m^0\,C}*1.590m + 17.3*10^{-6}\frac{\mu m}{m^0\,C}*1.41575m - 7.5*10^{-6}\frac{\mu m}{m^0\,C}*3.015m)$$

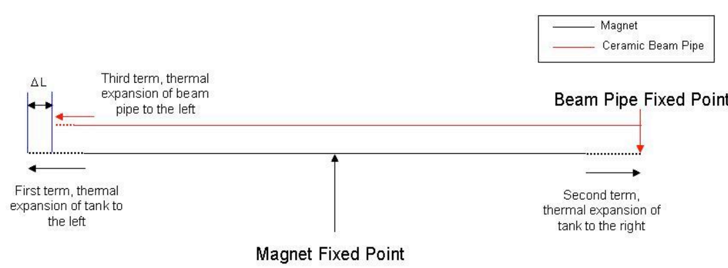


Figure 1 – Explanation of thermal expansions. The beam pipe is fixed on the right side of the magnet, which means its fixed point expands to the right first, before the tube itself actually expands to the left (illustrated by the red dotted line). The overall sliding distance of the fingers with respect to the magnet tank is indicated by ΔL.

Figure 1 explains where the three different terms originate from. It can be seen that the theoretical thermal expansion should be about 8.23 mm. During the bake-out process, it is possible that higher temperatures are reached, and if the previous calculation is performed assuming a temperature of 350$^0$C, a thermal expansion of 9.70 mm is achieved. However, it is possible that the beam tube and tank are not the same temperature, and in the worst case scenario that the beam tube did not undergo an expansion while the tank did, the fingers would slide a maximum of about 17mm. Figure 2 illustrates how the bake-out process affects the fingers in the original design.

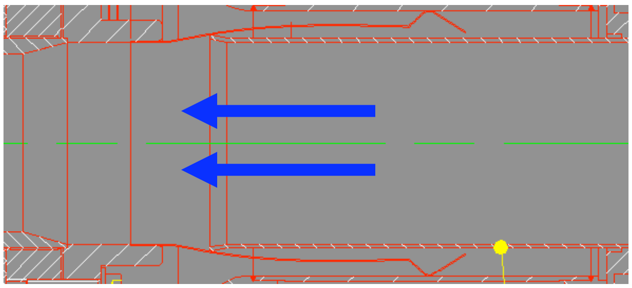

Figure 2 – Original AutoCAD assembly of the finger assembly. The blue arrows indicate the direction that the *fingers* move relative to the inserted cone. In this design, stress is relieved during the bake out process, before the fingers slide back into place when the magnet has cooled back down to room temperature.[6]

An additional problem introduced by the bake out process is that once the magnet enters the oven, it is completely closed off to the outside environment. It is impossible to know for sure how the different parts behave during the bake-out and cooling process. There is no way to see if the RF fingers continue to make solid physical contact after the bake-out process has been completed.

### *Cold-Welding*

Originally, due to a Copper/Gold physical connection (between the fingers and tube insert), cold-welding was observed. It was physically hard to take apart the magnet, as the fingers and cylinder had fused together where contact was made. To solve this problem, the end of the cylinder was plated with Rhodium. This eliminated the issue of cold-welding, as well as reducing the friction while the fingers would slide over the cylinder during the bake-out process.

### *Electrical Requirements*

The connection made between the beam tube and the insert tube must have a low electrical resistance in order to reduce the overall beam impedance.[7] The actual resistance of the fingers needs to be experimentally tested in order to fully quantify the effect of the gold covering on stainless steel. However, it is estimated that a total DC resistance of 2 mOhm/meter will give a low enough beam impedance for the fingers.[8] To provide adequate contact force between the fingers and the cylinder insert, it has been found that 40 grams of contact pressure is adequate.[9]

### *RF and Vacuum Requirements*

Possible designs for the fingers are limited as well by many stringent RF and vacuum requirements. To avoid possible resonance cavities, contact between the fingers and the cylinder should occur at the very edge of the cylinder. The device is designed to work up to approximately 1GHz, and the wavelength of this can be easily calculated:

$$v = f\lambda$$

$$3*10^8 = 1*10^9 * \lambda$$

$$\lambda = 0.3m$$

With a wave length of only 30 cm, if contact was made even 1 cm away from the end of the cylinder, this is 3.3% of the wavelength, which will increase the impedance significantly.[10]

In addition, the fingers must "shield" the beam from RF losses to the surrounding cavities. The less space between each individual finger, the lower the RF losses will be. However, the entire beam tube in the kicker magnets must be pumped out through the gaps in the RF fingers. There are no pumping ports included along the ceramic beam tube. In the current design, there is approximately 1020 mm$^2$ of pumping space (not accounting for slight 3-dimensional effects) which allows for adequate pumping.

In other inter-connects of the LHC, it has been specified that the beam pipe should not taper at an angle larger than 15$^0$.[11] This restriction is also valid for the finger contacts and the angle that the fingers form should not be larger than 15$^0$.

In addition to this, the entire magnet will operate under an extremely high vacuum of approximately 10$^{-11}$ mbar, which limits many aspects of the design and material selection.[12] Materials which are known to outgas cannot be used in this part.

*Assembly Considerations*

Due to the long length of the ceramic beam tube, the piece is very difficult to manufacture. Because of the extrusion technique used in the manufacturing process, it is unclear if the tube is completely concentric or not. Similarly, it is assumed that the tube is not completely straight, though detailed measurements of these two values have not been taken.

In addition to these issues caused in the manufacturing process, during the assembly process of the kicker magnets it is possible that the parts are not aligned perfectly according to the original design tolerances. It has been estimated that the center of the beam tube may be misaligned by a maximum of 10 mm with respect to the center of the tank.[13] For these reasons, any design used must be quite flexible and be able to tolerate significant displacements from original specifications.

## 3. Previous Design Analysis

*Deformation and Installation Issues*

Upon looking at RF fingers extracted from the magnets, it can clearly be seen that some plastic deformation has occurred. Some of these issues appear to be caused during installation, while some appear to be caused by the thermal expansions and/or errors in alignment of the beam tube. Figure 3 shows clearly how one finger, during installation, ended up on the incorrect side of the cylinder insert. This both partially obstructs the beam pipe as well as permanently deforming the finger itself.

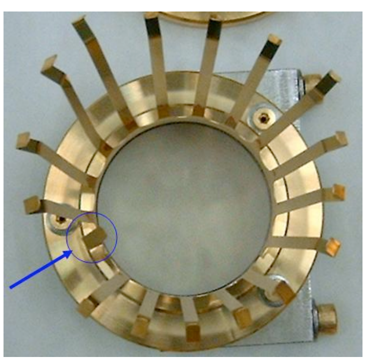

Figure 3 – Picture of a MKI RF finger contact used which has been extracted from a kicker magnet. The circled finger was clearly installed incorrectly and on the incorrect side of the cylinder, resulting in permanent deformation and partial obstruction of the beam pipe. The mechanical properties of the individual finger have now been altered.

Due to possible misalignments in the set up of the kicker magnets, more plastic deformation has been observed. Figure 4 shows how some of the fingers are rounded outwards, where the contact force has been continuously applied. Using FEA analysis in AutoCAD and approximating small displacements of the cylinder insert with the current design, it was observed that an offset of only 5 mm increased the contact force significantly (from 2.1 N to 11N), and moved the fingers into the plastic deformation regime (stresses around 500 N/mm$^2$, where elastic limit is 200 N/mm$^2$).

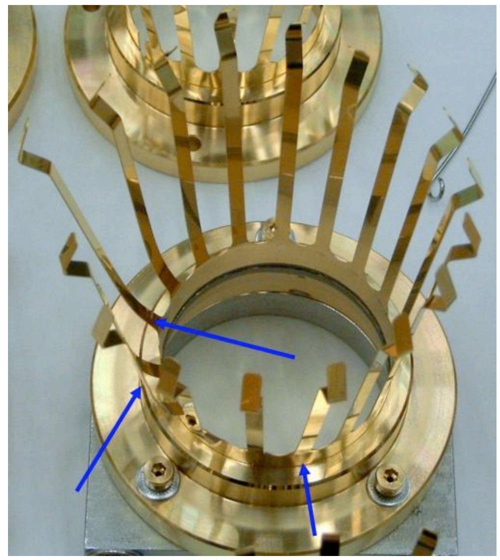

Figure 4 – The arrows indicate where plastic deformation has occurred in the fingers, as some fingers are bent outwards. Interestingly, for these fingers it appears that only the fingers on one side are plastically deformed, suggesting that the beam tube was laterally off-centered, which would result in this deformation. After extensive work with the fingers in general, it is the author's estimation that the offset was in the range of 4-10 mm.

While the fingers are produced from flat stock metal, they make contact with the curved surface of the cylindrical insert. In reality, instead of electrical contact occurring along the entire width of the fingers, contact most likely occurs in only one place. However, it has been hypothesized that after installation and bake-out, some angular deformation occurs in the fingers, which could even further reduce the contact area of each finger.

One important aspect that should be kept from the old design is the tolerance on the screw holes for the cylinder insert. The screw holes allow for some small radial movements (±1 mm) which help to slightly offset the negative effects of the beam tube being mis-aligned.

### *Number of Contacts*

The original design called for 34 fingers, but this was reduced by a factor of 2 due to vacuum pumping concerns.[14] By reducing the number of fingers, the electrical properties have probably been affected in a negative way. The effect of poor contact from a single finger has now been amplified, and this could have a significant effect on the beam impedance. Similarly, the increased spacing of the RF fingers probably results in increased RF leakage to the vacuum tank.

### *Impedance Measurements*

When measurements are performed on the kicker magnets, it is hard to pinpoint exact causes of beam impedance. However, by checking values before and after bake-out, it is possible to infer what is going on inside the magnet. Recent measurements have shown that in one of the magnets, impedance actually increased after the bake out process.[15] In this magnet, power dissipation on the magnet increased by 20%, which may suggest that after the thermal expansion and contraction, the RF fingers made a less effective electrical contact.[16]

### *Material Issues*

The fingers themselves are made from Stainless Steel 316L, and are covered with gold (please see section 4 for a more detailed discussion of material properties). The fingers are designed to conduct the beam image current, which is expected to be high frequency but small in magnitude. Because of this, the majority of the current will travel along the surface of the fingers, not the interior. This is why the gold covering should significantly reduce the resistance of the fingers. However, currently there is only a 0.5 μm covering, which is not enough. Ideally, this value should be between 10 μm and 15 μm.[17]

### *Base of Fingers*

Contact is made between the base of the fingers and the beam tube through the use of Multi-Contacts, model MC-LAIII.[18] This piece is then screwed into the finger base, with three screws (Fig. 5). However, these screws provide the contact force for the electrical contact formed between the two pieces (not shown). It is possible that using only 3 screws is actually a source of increased beam impedance. The two conducting materials may not be fully in contact around the entire circumference of the circle, due to a lack of additional screws.[19]

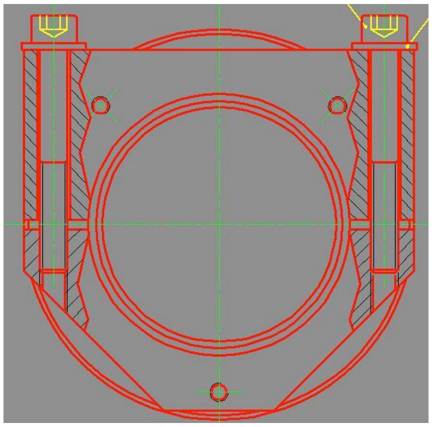

Figure 5 – Design for base of RF fingers.[20] While the three screws mechanically work fine, it is possible that the contact surface between the two pieces is not consistent.

## 4. Material Selection

### *Possible choices*

For many other interconnects in the LHC, a Copper Beryllium alloy is used. This material is chosen due to its high electrical conductivity and it's high modulus of elasticity.[21] However, the kicker magnets are unique in that their bake-out temperature is 300$^0$C, while the other magnets have a bake out temperature of 200$^0$C. Figure 6 illustrates the effect of the bake-out process on C17410 alloys (low resistance Copper Beryllium). If Copper Beryllium fingers were to be used, they would only have slightly greater than 50% of their original elastic properties. As well, this annealing process would occur while the fingers would be under stress, which could also have negative effects on the effectiveness of the fingers.

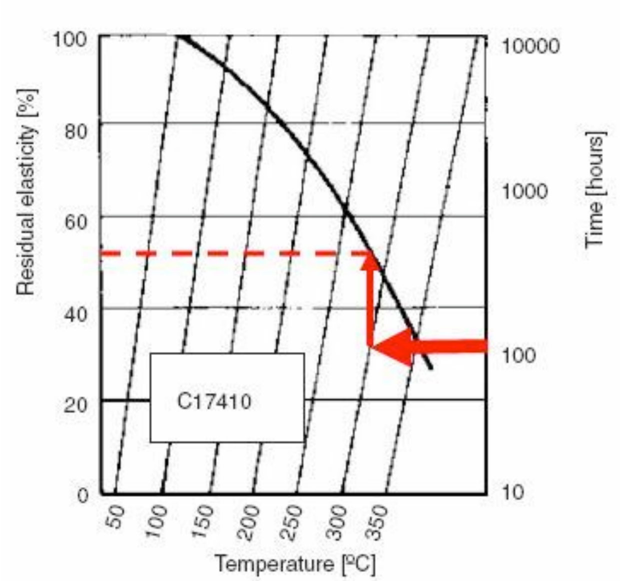


Figure 6 – The above graph shows the residual elasticity of C17410 (low resistance Copper Beryllium). If this material was used in the kicker magnets, it can be seen that fingers would only have slightly more than 50% of their original elasticity.[22]

A material with a higher melting point needs to be used in the kicker magnets in order to reduce the loss of elasticity during the bake out process. For this reason, Stainless Steel 316L was chosen. Table 1 shows a comparison in material properties of SS 316L and C17410.

Table 1 – Comparison of material properties between SS 316L and C17410.[23]

| | Modulus of Elasticity | Tensile Strength (Yield) | Melting Point | Resistivity |
|---|---|---|---|---|
| 316L | 193 GPa | 290 MPa | $1375^{o}$C-1400 $^{o}$C | $7.4 * 10^{-5}$ ohm-cm |
| C17410 | 138 | 700 MPa | $1050^{0}$C | $3.82 * 10^{-6}$ ohm-cm |

While C17410 would clearly be the ideal material to use, with the bake-out reaching at least 29% (if not higher) of the melting point of C17410, this material is not an option. Stainless Steel 316L was chosen due to its high melting point and ease of workmanship. Stainless Steel is also commonly used in vacuum applications, and has extremely low out-gassing, which is essential in the kicker magnets.

For the electrical contact, it is ideal to have contact between a relatively soft metal and a relatively hard metal. This allows a larger contact surface to be established. It has been found that the rhodium/gold contact interface works extremely well, as gold is a soft metal while the rhodium is quite hard.

## 5. New Design and Recomendations

### *Multi-Contact Option*

Some research was done into using multi-contacts, specifically the LA-CUT model (see Fig. 7).

Figure 7 – LA-CUT multi-contact design. These parts provide extremely low resistance connections with maximum flexibility.[24]

However, it was found that the products available did not meet the design specifications. One proposed design that involved multi-contacts used a sliding tube that would connect to the end of the beam tube, with the LA-CUT Model. However, the elasticity and performance of the LA-CUT contacts could not be guaranteed after bake-out, and it would be very probable that much of their elastic properties would be lost.[25] In addition, the fact that the beam tube is not perfectly concentric, nor perfectly centered would cause issues with these parts. The LA-CUT model is designed to allow for approximately ± $2^{0}$ of angular mis-alignment.[26] If the maximum possible tube length is used, this translates into an acceptable displacement of about 4 mm. These issues, combined with the complexities surrounding designing an entirely new contact made it not worthwhile to use multi-contacts in this part of the magnet.

### *Modification of the Old Design*

After much thought, it was decided that the best solution would be to simply modify the existing design and attempt to correct all the problems mentioned in section 3.

The major change with the new design is that the inserted cylinder should be reduced in length by 40 mm. Otherwise, the cylinder should be the same as the original design (with the rhodium covering), though it is imperative that the quality of the rhodium covering is extremely high and that it is polished to specifications, to decrease electrical resistance.

By moving the cylinder back, this allows much more freedom with the design. Firstly, since contact will now occur much farther from the base of the fingers. The chance that slight misalignments will results in plastic deformations should be decreased. As well, this increased length allows more fingers to be added to the design and less space in between the fingers, while still having the same amount of surface area available for vacuum pumping. Although the image current now has to travel about 40 mm more, this should have little effect on the RF properties.[27] With this new setup, it is now possible to have 40 fingers, each of width 2.5 mm, thickness 0.5 mm and a separation of 1.5 mm. Neglecting 3D effects once again, this gives about 2880 $mm^2$ of pumping space, still much greater than the original 1020 $mm^2$. However, this should not cause a problem concerning RF leakages if the surface area is compared to other LHC interconnects. Many LHC interconnects have approximately 3300 $mm^2$ of open surface area, which does not cause any problems concerning RF leaks.

The large increase in the amount of fingers should decrease the electrical resistance significantly, as well as decrease the effect of a faulty contact with one individual finger. Increasing the thickness from 0.3 mm to 0.5 mm, as well as decreasing the width from 3.5 mm to 2.5 mm should help with the angular deformation problems. Decreasing the width of the fingers allows there to be more space for pumping, and allows the number of fingers used to be increased. Due to the radial contact, there is generally only one point of contact. Increasing the thickness of each individual finger should decrease the amount of angular deformations, which should result in a larger surface area of contact.. Increasing the amount of fingers by more than a factor of two should significantly reduce the beam impedance caused by the finger contacts as well as reducing the effect of a single faulty contact in one of the fingers.

It is also recommended that the number of screws attaching the base of the fingers to the clamp below should be increased from 3 to 8. This should help decrease the electrical resistance between these two parts. In addition, on many other connections similar to this one there is a small amount of material removed behind the welding of the fingers to reduce the chance of virtual leaks occurring (see Fig. 8). Whether or not this is required for this part needs to be examined further.

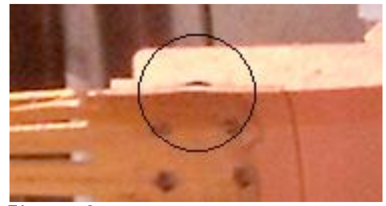

Figure 8 – Small section of material cut out behind where the fingers are welded on to their support. This allows some gases to escape, and can prevent virtual leaks.

It is also imperative that the gold covering of the fingers be thicker than what it was before (0.5 μm). 15 μm of gold on top of the stainless steel should be adequate.

### *AUTOCad Design*

The finger design itself has changed slightly, in order to accommodate the new points of contact. With a thicker finger, it was also necessary to have small deformations, so that plastic deformation would not occur. The angles and general design originated from other contacts currently used in the LHC.[28]

The new design should be able to withstand the bake-out process quite easily. The stress felt in the finger should decrease as the fingers move away from the cylindrical insert, and as the magnet cools back down again, the fingers will slide back into place, increasing contact pressure once again.

Many designs were attempted, and the finger below (Fig. 9) is the best solution that has been found so far. More experimenting should be done with designs, perhaps with a thickness of 0.4 mm, which may allow more freedom with the design. By having a thickness of 0.4 mm, there should still be less angular deformations than the original design, but the fingers will be able to undergo a larger displacement with less stress. With a thickness of 0.4 mm it may be easier to create a design that is more forgiving if the magnet is not assembled completely to specifications, and whose stresses and contact forces are more consistent over a wider range installation errors.

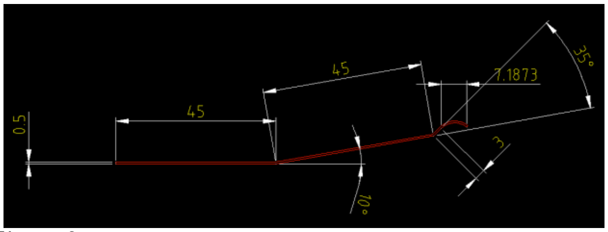


Figure 9 – New AutoCAD design for an individual finger.

### *FEA Analysis*

Within AutoCAD each design was modeled using FEA analysis, to analyze the contact pressure and the internal stresses. Within the program, the modulus of elasticity was taken to be 193 000 N/mm$^2$ (from Table 1, as 1 GPa = 1000 N/mm$^2$) and the elastic limit was taken to be 200 N/mm$^2$.[29] The width of each finger was also specified to be 2.5 mm, as earlier stated. Figure 10 shows an image of the electronic modeling, and the contact pressure observed was 0.58 N (0.59g) and the maximum stress in the finger was only 108 N/mm$^2$, well below the elastic limit. With this design, even if the fingers are 5 mm too close to the cylindrical insert, the maximum stress is still only 170 N/mm$^2$ (and contact pressure increases), still within the elastic limit. If the fingers are 5 mm too far away, the contact pressure drops to roughly 0.2 N (20g), which could cause an increase in impedance. More testing or analysis needs to be done to see the effect on the fingers if the magnet is not assembled to specifications.

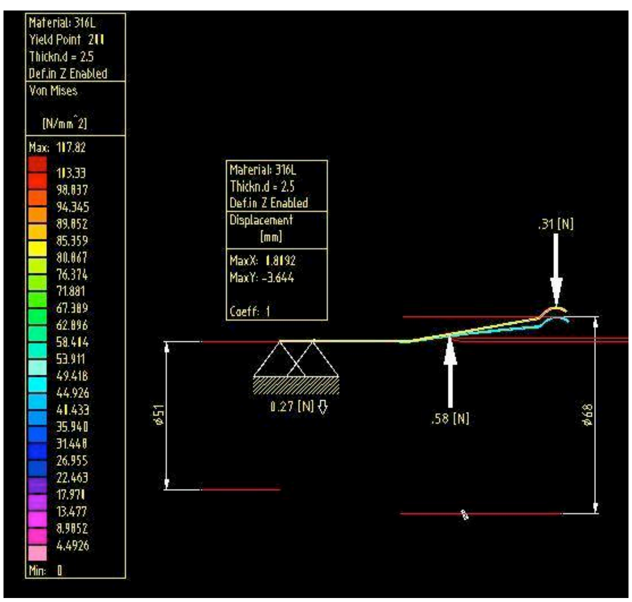


Figure 10 – FEA Analysis of a single finger. The finger is well within acceptable tolerances for both contact pressure and stress.

### *General Recommendations*

There are several general processes concerning the MKI RF contact fingers that could be improved as well. Firstly, great care needs to be taken during the installation of the fingers to ensure proper contact is made. As well, during installation, it would be extremely useful to know how off-centered the beam tube actually is. The fingers should also be tested extensively before being sealed in their respective magnets.[30]

## 6. Conclusions

While the MKI RF contact fingers are a seemingly insignificant part of the LHC, a poor design could still have extremely large consequences. After careful analysis of the original design, some key changes need to be made. To summarize, more fingers should be added with each finger being narrower and thicker, and the stainless steel fingers need to be covered in a thicker layer of gold. As well, the length of the cylindrical insert should be shortened, and a different design for the fingers themselves has been made. These simple changes should increase the effectiveness of the MKI RF contact fingers significantly as well as increasing the effectiveness of the magnet itself.

## Acknowledgements

In addition to everyone cited, special thanks should be given to Benoit Riffaud (the original designer) and Mike Barnes (advisor) for countless conversations about the fingers and much help with the design and computer modeling.

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[30] Contact Alexis Vidal (AT/VAC - CERN) for methods used on other contact fingers.