COMMISSIONING AND UPGRADE OF AUTOMATIC CAVITY TUNING MACHINES FOR THE EUROPEAN XFEL

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Abstract

For more than 20 years DESY has gained experience in tuning cavities of TESLA [1] shape nine cell cavities for FLASH [2] to field flatness and concentricity.

Based on this experience four automatic cavity tuning machines were developed and built by a collaborative effort among FNAL, KEK and DESY [3] to support the high throughput of series cavity productions necessary for new projects like the European XFEL [4], the ILC project, Project "X" and further SRF based future projects.

In the meantime two machines were delivered to the collaborative partners KEK and FNAL. The remaining two machines at DESY, are regularly used since several months. A large number of cavities of different types and at different production stages have been automatically tuned for FLASH and also in preparation for the European XFEL series cavity production starting this summer.

INTRODUCTION

Typical tuning methods [5] are based on special tooling to manually obtain plastic deformation of every cell by an expert operator. This is a very time-consuming procedure. It is not adequate for cavity series productions needed for SRF-based projects like the European XFEL.

Four completely new designed machines were developed, built and successfully commissioned until 2009 at DESY by a close teamwork with FNAL.

Due to this operational experience and the requirements of the European XFEL cavity specification, it became necessary to improve and upgrade several components of the automatic cavity tuning machines and their control software [6].

These upgrades mostly impact the accuracy and the diversity of machines to get the ability to tune cavities in different production stages – from the semi-finished, just electron beam welded cavity, over the completely prepared and chemically treated cavity with welded ring and bellow, up to the completed cavity, welded in helium tank.

These upgrades have a multiple influence on the safety concept of the machines.

All changes of the machines have to comply with the essential health and safety requirements and have to be designed, built and documented in accordance to the Machinery Directive of the European Community (EC). In June 2010 the 2nd revised version of the Machinery Directive of the European Community (EC) was validated. Because of the delayed official delivery date of machines to the cavity vendors new safety measures had to be taken into account.

In the following the several upgrades with their reasons and targets to the functionality of the automatic cavity tuning machines are described in detail.

MAJOR UPGRADE OBJECTIVES

From the gained experience we decided on several necessary upgrades.

The functionality of machines was expanded by:

- Tune a cavity with welded ring and bellow.
- Accomplish a bead pull measurement on a cavity welded in a helium tank.
- Enable machines to operate an automated calibration procedure.

It is well known that the welding procedure of a helium tank changes the field flatness by deformation of a cavity in a slight but not irrelevant percentage. To guarantee planed accelerating gradients, the field flatness - after welding of ring and bellow - needs to achieve 98% before tank welding.

To obtain these aims it is necessary to increase the accuracy not only for feedback measurements during the entire tuning procedure but even for the cell tuning and alignment itself.

The accuracy of machine was enhanced:

- Total resolution of eccentricity measurement device better than 0.1mm.
- Increase precision of entire tuning frame.
- Enhance plastic deformation range of jaw units.
- Increase precision of cavity alignment tool.

TUNING FRAME UPGRADE

The tuning frame is designed modularly. All assemblies including electronic enclosures are mounted to an aluminum alloy cast base plate. The plate itself only captures the weight of subassemblies. The entire design is done in a way that no counter forces are applied to the base plate.

Figure 1 shows the tuning frame with the base plate and the three vice units. The tuning frame consists of three equal vice units, arranged in a 120°angle. Each vice unit has two tuning arms mounted on a rotary axis. Via a stepper motor and two gearboxes the distance between the arms can be changed for squeezing or stretching cavity cells. The tuning force can reach 90kN per vice unit.

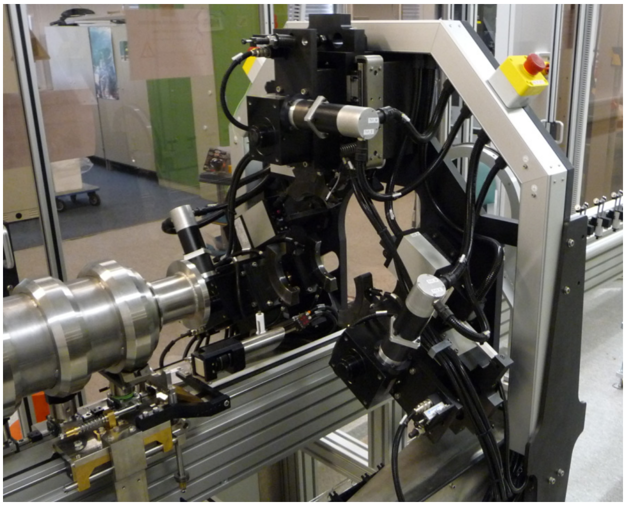

Figure 1: Upgraded tuning frame with new vice units.

Four major upgrades were implemented to the most important components of the tuning machines to enhance tuning functionality and accuracy.

The possible range of vice units was increased as well as measurement devices were improved. With the customized tuning machine software inner stress of cell material –caused by different welding and machining procedures– can be relaxed by iterative stretching and squeezing of cells by a raised deformation range.

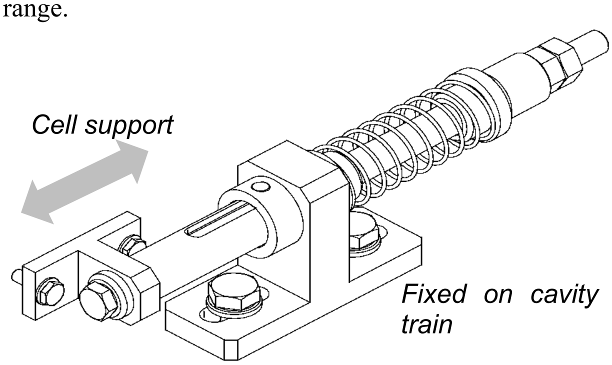

Figure 2: Sketch of centering unit for cavity on the train.

Feedback forces due to cavity train support by straightening and bending of single cells were eliminated. A new centering unit Figure 2 keeps the cavity well positioned and simultaneously free to move during tuning procedure. This allows moving the cavity several millimeters in both directions of the horizontal axis. Further new supports of cavity train were installed.

Now cavities in all production stages, with different deadweights, are fully “floating” on the cavity train. This allows tuning and bending any cell of the cavity by relatively large angles without the appearing of additional tuning forces caused by the load of entire cavity. In the same step, the cavity train was modified in a way that cavities with welded ring and bellow (Figure 3) fit to the train.

A laser beam which is sent from the short side beam tube flange to a mirror mounted at the long side beam tube flange is used to check the straightness of the cavity. The reflected laser beam is projected on an elliptical target fixed to a 45° notched tube, comparable to a periscope.

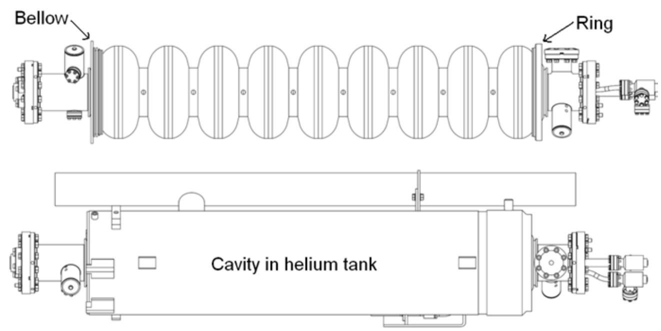

Figure 3: Sketch of cavity with ring and bellow (above); Cavity in helium tank (below).

Through digital image processing the position of the laser spot on the target can be located. An algorithm in the cavity tuning software calculates additional deformation for individual cells in defined directions. This system was upgraded with a special magnifying mirror, which carries the optical refraction layer on the outer surface. The measurement range was customized to enhanced bending angles and deformation values while absolute resolution was increased. Failures caused by optical refraction because the laser beam is passing through different materials are eliminated.

One major problem is to tune the end cells and to achieve the aim of 98% field flatness while the concentricity deviation of cavity has to stay in 0.1mm or smaller.

They differ geometrically and by their length. Connecting end flanges and the conical disc which is part of the helium vessel are welded next to the end cells. HOM couplers and main coupler port restrict space for the jaws.

This makes it difficult to tune the end cells and mainly to obtain a tuning force which is symmetrical to the cells.

New improved tuning end rings were designed and successfully tested.

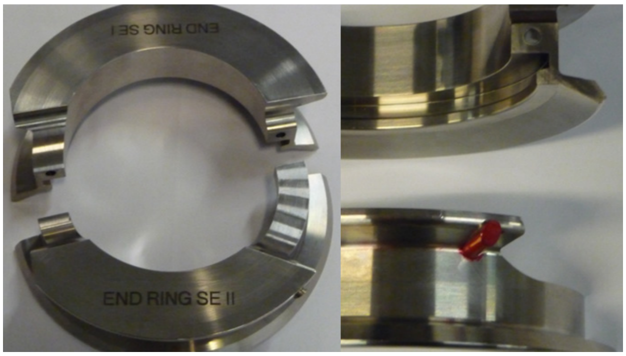

Figure 4: New set of tuning end rings, notice the red marked contact point.

The outstanding properties of the tuning end rings are the new lateral connections, asymmetrical cut outs related to the main coupler port and HOM and additional contact points to jaws (red marker; see Figure 4).

The special shape of the new tuning end rings with additional contact points to jaws allows deforming of end cells by up to ±15mm from theoretical length of cells and simultaneously assuring a defined and symmetrical application of force to cells in tuning procedure. It took several iterations and a lot of experimental effort to optimize the tuning end rings to all requirements.

All four described upgrades of the tuning frame together with the new and improved tuning software – provided by FNAL – now enables the cavity tuning machines to automatically tune different production stages of cavities to 98% field flatness.

UPGRADE OF BASE FRAME

All components of the tuning machines are mounted to the 5.20m long base frame.

The whole structure of base frame was reinforced with sturdy steel pillars fixed to the ground. This solution was necessary to enhance stability, in particular for the eccentricity measurement device. By this upgrade of base frame a new cable guiding system for electronic rack to machine interconnection cables was necessary.

ECCENTRICITY MEASUREMENT DEVICE

During the entire tuning procedure, the high resolution measurement of the geometrical cavity properties like length and straightness of cavity and concentricity of the cells are a substantial requirement needed to achieve the demanding tuning results.

All these mechanical values of the cavity are referred to reference planes of the cavity on the connection end flanges. Furthermore, these reference planes are used to align and weld ring and bellow and helium tank to the cavity (see Figure 3).

The cavity alignment in the module cavity string is also performed with the help of these reference planes by a 3D-transfer measurement.

The whole measurement procedure is accomplished by 11 distance meters and two laser sensors. The middle locations of equator diameters are measured with nine high resolution potentiometric linear distance meters. A similar system with identical sensors is used to reach the center locations from the two beam tube flanges.

The length and perpendicularity of reference plane is calculated by triangulation of different distance values measured with a precision laser distance detector.

To achieve the aims of resolution, longstanding stability and enhanced functionality, the entire mechanics of the eccentricity measurement device was completely redesigned.

To measure the cavity, it is brought into a given measurement position by two lift units. These lift units (Figure 5) have been totally renewed and reinforced. They allow lifting a cavity with welded ring and bellow into the measurement position.

The idea to compensate the bending of cavity by gravity in the measurement position with adjustable springs was completely superseded by a software solution in cavity tuning software.

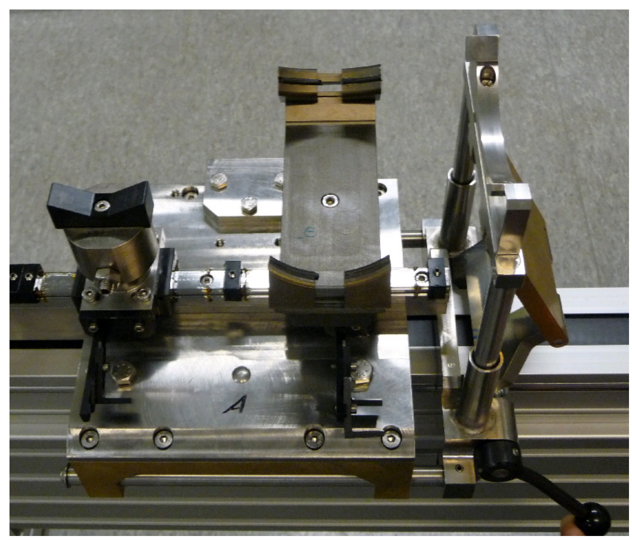
Figure 5: Heavy duty lift unit seen on the right side. It is manually operated.

The entire measurement device is now mounted on two sturdy steel pillars fixed to the ground. They also carry the base frame with the cavity train and lift units. This significantly increases the stability of the entire device.

Gearings, drive chassis and measurement bar were superseded as well by a full steel construction (Figure 6).

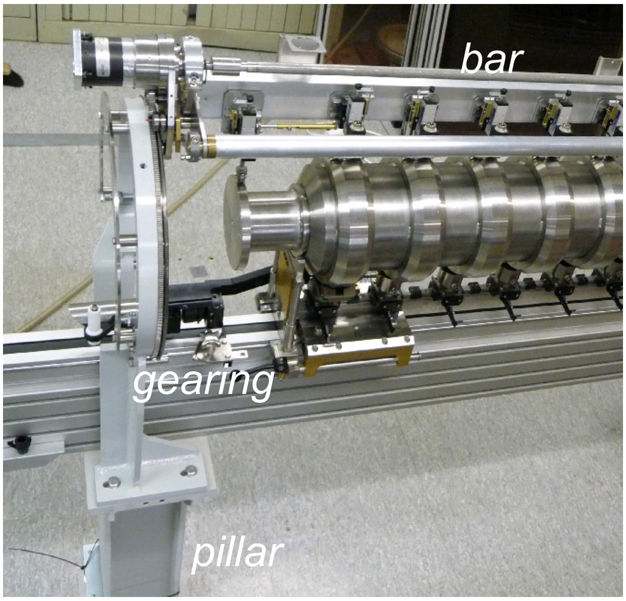

Figure 6: New design of gearing, drive chassis and measurement bar supported by the steel pillar.

The eleven sensor units with distance meters are now guided by two precision linear slides.

The data acquisition software of eccentricity measurement device, supplied by FNAL, was updated. Now, measurement values are taken in continuous motion synchronized to the measurement angle. Vibrations caused by stop and go operation to take single data points were eliminated.

A new calculation model with a specialized algorithm to locate the cells' centers in comparison to the cavity axis as well significantly enhances the total resolution of the eccentricity measurement device.

BEAD PULL SYSTEM

A new requirement to the tuning machines for European XFEL cavity fabrication is the bead pull measurement for cavities already welded into the helium tank.

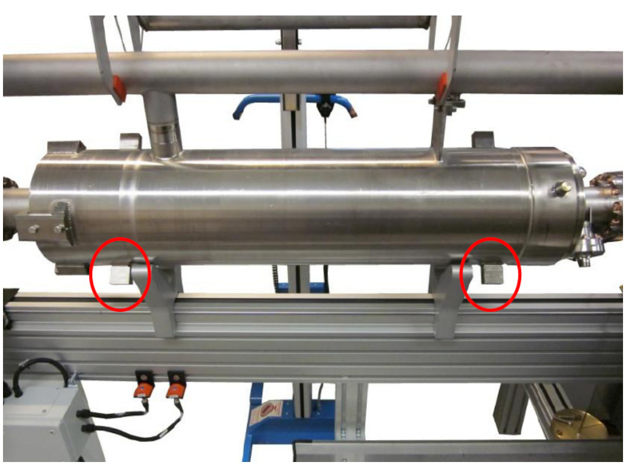

Figure 7: Cavity in a helium tank on new supports.

Because of the bigger diameter they do not fit to the existing cavity train. The existing bead-pull-measurement system was upgraded with a support for positioning the cavity in the helium tank on the base frame in order to realize the bead pull measurement after helium tank welding. Figure 7 shows a picture of the new supports carrying a cavity in a helium tank in fixed measurement position on the base frame of the tuning machine.

CAVITY LIFTER AND GRIPPER

Figure 8 shows an updated cavity lifter carrying a cavity in a helium tank. Now it is also possible to position a cavity on the new supports of the cavity tuning machines which was already welded into a helium tank.
Furthermore, the cavity lifter was upgraded with an additional set of grippers. This set of gripper enables the lifter to carry and position the dummy cavity for machine calibration. Figure 9 shows a new gripper and an updated cavity lifter carrying a dummy cavity for machine calibration.

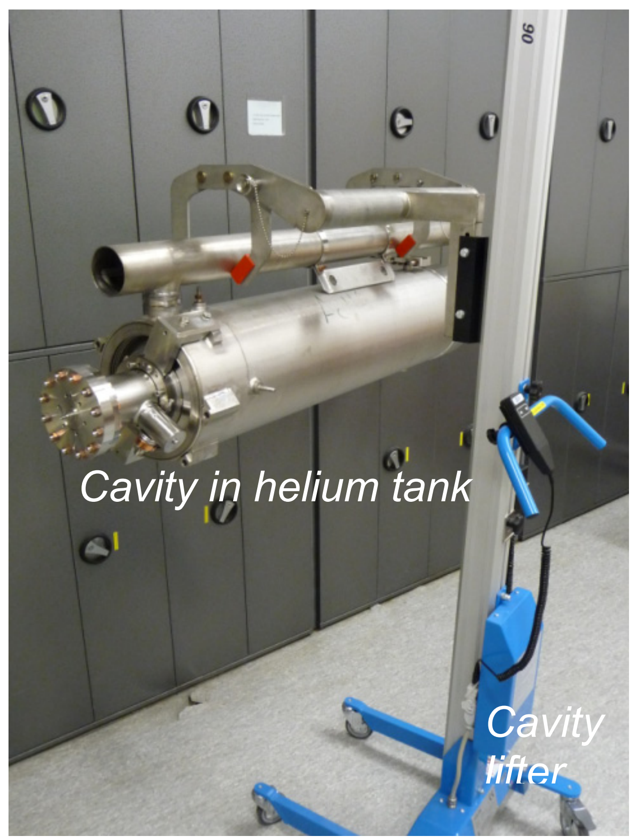

Figure 8: Cavity lifter carrying a cavity in a helium tank.

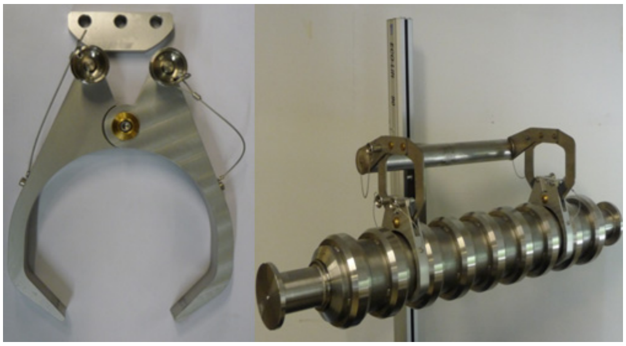

Figure 9: Gripper and cavity lifter carrying a dummy cavity for calibration.

UPDATED RF CABLE GUIDING SYSTEM

The RF-cable guiding system was updated to meet new requirements for the cavity in helium tank bead pull measurement. The existing system could not be used as the measurement is not done on the cavity train.

The entire cabling system has to fulfill requirements like minimum possible bending radius of cables, limitation in total length of cables and minimization of reversible plug connections. These requirements are to prevent phase shifts – caused in reflections - and undesirable losses. Figure 10 gives an overview on new realized solution.

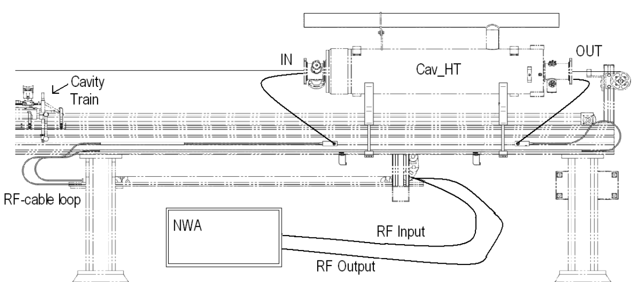

Figure 10: Sketch of new RF-cabling for cavity in helium tank.

For standard cavities in all production stages - without helium tank RF input and RF output cables coming from the network analyzer - are directly connected to the cavity.

During a measurement of a cavity in a helium tank RF cables are connected to feed throughs in park position on the cavity train. The train is driven away from measurement position. The RF cables are guided back in a loop through the cable guiding system passing by the base frame until they get directly connected to the cavity in helium tank.

This solution allows additional measurement without a further network analyzer or RF switches. The positioning of the cavity and the measurement procedure could be realysed by a new skript of tuning machine software The measurement is fully automated.

SAFETY FENCE: ENTERING CONCEPT

The 2nd. Revised Machinery Directive 2006/42/EC of the European Community (EC) is valid from December 29th. 2009 and has to be applied to the upgraded tuning machines.

This is, apart from the technical upgrades, the major reason for several changes in software and electronics.

All changes of the machines have to comply with the essential health and safety requirements and have to be designed, built and documented in accordance with the Machinery Directive of the European Community (EC).

Caused by the enhancement of the machine functionality the number of necessary enterings into the machines' safety fence were increased.

A new entering concept was mandatory. The system realized now operates completely software controlled and monitored. To fulfill the safety requirements the motor currents of several stepper motors need to be physically interrupted during entering into safety fence. The related challenge is to keep positions of different axis adjustments and not to trip the emergency trip system or cause errors in the tuning machine's software.

The existing emergency trip system, the motion inhibit system and the cavity tuning machine software [6] were upgraded with several safety devices for monitoring and controls. Actually all enterings are released, monitored and inverted after entering by software.

After completion of the entire machine documentation for mechanics, electronic devices and software the declaration of conformity according to EC directive of machinery in 2nd revised version will be signed in the end of 2011.

SUMMARY

Effectively, one of two cavity tuning machines for the European XFEL cavity series production is upgraded by DESY. It is under commissioning and testing. First test results are encouraging.

Functionality and accuracy of the machine was enhanced. It is now possible to measure and tune semi-finished, just electron beam welded cavities as well as completely prepared and chemically treated cavities with welded ring and bellow. Furthermore, the bead pull measurement of a completed cavity which is welded in a helium tank can be performed on the same machine. Data transfer and storage in cavity data base works fine.

The achievable field flatness for all different production stages of cavities was gained to regularly 98% at fully automatic operation of cavity tuning machine software without any encroachment of operator.

The second machine for series production will be upgraded during August 2011.

From October 2011 on, the reference cavities from European XFEL cavity vendors will be tuned at DESY by vendors' machine operators. Early in 2012 the hand out of machines to the cavity vendors will follow.

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