MECHANICAL DESIGN OF AUTOMATIC CAVITY TUNING MACHINES

Jan-Hendrik Thie, A. Goessel, J. Iversen, D. Klinke, W.-D. Möller, C. Müller, D. Proch
Desy, 22603 Hamburg, Germany
Ruben Carcagno, T. N. Khabiboulline, S. Kotelnikov, A. Makulski, J. Nogiec, R. Nehring, M. Ross
W. Schappert Fermilab, Batavia, IL 60510 USA

Abstract

Since 15 years a prototype semi automatic cavity tuning machine is used at DESY to tune field flatness and concentricity of TESLA [1] shape nine cell cavities for FLASH [2]. Based on this experience a further development work was done in a collaboration effort among FNAL, KEK and DESY to support the high throughput of series cavity productions necessary for new projects like the European XFEL [3], the ILC project, Project "X" and other SRF based future projects. Initially four machines were built within the collaboration at DESY. Two of them will be delivered and operated by the cavity vendors for tuning the XFEL cavities. The remaining two machines are delivered to FNAL for commissioning. One of them will be passed on to KEK.

In the following the mechanical design and functionality of these machines is described. Special attention refers to safety aspects for the machines operation at industry and the fulfillment of requirements according to the EC directive of machinery.

INTRODUCTION

For a β≈1 multi-cell SRF cavity, the fields in adjacent cells must be π radians out of phase with each other and the particle must cross a cell in one-half of an RF period. This flat field profile is achieved when the cells are properly tuned relative to each other and the cavity frequency is equal to the design frequency (e.g., 1.3 GHz for XFEL cavity at 2K in vacuum). In addition, the tuned cavity must meet dimensional tolerances such as length, straightness and concentricity of cells.

Cell-to-cell tuning is usually accomplished by slightly plastic deforming every cell until the desired cell frequency is achieved. This procedure is normally foreseen for every cavity after fabrication or after relevant preparation steps like etching or deformations caused by heat treatments or welding.

Typical tuning methods [4] are based on special tooling to obtain plastic deformation of every cell manually 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 XFEL.

An alternative method is shown by the semi automated prototype tuning machine which is used at DESY since several years. The function of the machine is based on three independent vice units to squeeze or stretch a cell while keeping the cavity straight.

The major principle of this machine is the basis for a new series of high level automation tuning machines developed within the collaboration of FNAL, KEK and DESY.

The new machines are expected to significantly reduce the duration time of the tuning procedure, also they have to be operable by non RF-experts.

The use of the machines is not limited to laboratories and institutes. It is foreseen to operate them at industry.

Among the collaboration all four machines were mechanically designed and fabricated by DESY including all actuators and sensors for the new automation concepts based on the yielded experience.

FNAL is providing four complete improved control sets with electronic racks, operating stations and measurement techniques including all hard- and software. The totally renewed Software including calculation algorithms by FNAL is an important contribution to the aimed objectives.

OVERALL CONCEPT

The main component of the new entire tuning machines (Fig.:1) is the Tuning Frame (TF) which accommodates all mechanics, such as vice units, sensors and actuators needed for plastic deformation of cavity cells. After several optimizations the "frame" became an aluminum alloy cast plate.

All components of the tuning machines are mounted to the 5.20m long Base-Frame (BF). It consists of several aluminum alloy extruder profiles. This guaranties high modularity and decreases the weight of machines.

A major component for feedback in tuning procedure is the Eccentricity Measurement Device (EMD). With 11 linear distance generators and two laser sensors it not only gives information on concentricity of single cells to cavity axes, it also displays length of cavity and perpendicularity of reference planes, of end flanges and beam tube flanges.

The measurement of field flatness is done with a Bead-Pull-System (BPS). Due to the total length of the BF and to reduce the oscillation of the bead, the system is not a string loop, but a string pulled from a reservoir. The Network-Analyzer (NWA) is connected to the cavity via RF-cables in a cable guiding system.

A completely new designed device of the machines is the Cavity Alignment Tool (CAT). It gives the possibility to measure (qualitatively) the direction of cavity deformation compared to its straightness during the tuning procedure.

Figure 1: Entire Cavity Tuning machine with the machine housing. The door at the cavity insert position is open.

During all steps of the tuning procedure the cavity is kept and moved by a Cavity Train (CT) with several supports and lift units which bring the cavity into a defined position for eccentricity measurement.

For safety reasons the entire machine is secured by a machine housing with safety gates. To implement this, the tuning procedure needs to be optimized to a minimum of hand operation to decrease the number of entries

TUNING FRAME

The TF (Fig.:2) 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 base plate.

Figure 2: The picture shows the Tuning Frame with the base plate and the three vice units. On the cable channel the emergency switch is assembled.

This design allows assembling and disassembling the whole TF from the machine. Thus, easy assembly and disassembly and therefore easy transport is possible. In addition the open structure of TF allows easy maintenance.

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. Both arms are free to move around the rotary axis. They are kept in place by low pre-stressing spring cradles.

Figure 3: Tuning jaw with exchange part and proximity switches.

Fitted to the tuning arms are special tuning jaws (Fig.:3) with two proximity sensors and in two cases additional sensors for exchange parts. These exchange parts are removed or added for tuning end-cells or normal cells of XFEL cavities. They are necessary or allow tuning of end cells where e.g. room for the HOM couplers or main coupler port flange is needed without changing complete jaws. The jaws are, restricted to an angle of a few degrees, free to move around their fixing stud. The complete vice units are moved towards the cavity with linear actuators. A system of protective shields and connection rings to end cells, such as the proximity switches of jaws, accomplish seeking of vice units to cavity in a way the cavity stays free to move a little.

Altogether the cell which will be tuned in the frame is free to move in every axis during plastic deformation. There is no reaction force additionally brought to the cell. Actually the G-forces are kept by special supports (Fig.:5) of cavity train. By this practice it is possible to deform different areas of a cell deviant and thus to tune a cavity straight.

BASE FRAME

To keep the machines modular during development phases and to allow several numbers of shipments and commissioning at different locations, all components of the entire tuning machines are mounted to a base-frame consisting of several aluminum alloy extruder profiles. Compared with the prototype machine developed 15 years earlier, the total weight was decreased by 70%.

The machine design is divided into two major assemblies:

- The tuning frame (TF) with all needed actuators and electronic enclosures.

- The Base Frame including EMD, cavity train and bead pull system.

ECCENTRICITY MEASUREMENT DEVICE

In the entire tuning process, a feedback of mechanical properties like length and straightness of cavity and concentricity of the cells is very useful to achieve a good tuning result.

All measured 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 the weld ring and bellow of the helium vessel to the cavity. The cavity alignment in the module cavity string is also performed with the help of these reference planes.

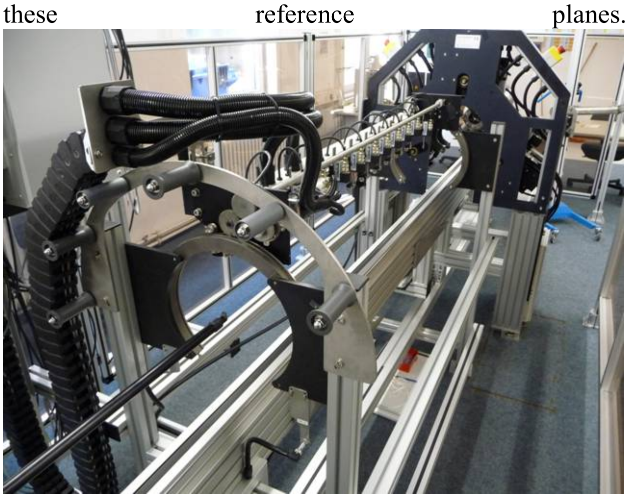

Figure 4: Eccentricity Measurement Device, showing the rotatable arm with the distance generators.

In the eccentricity measurement device (Fig.:4) the cavity is brought into a given measurement position by two lift units. This is done automatically without additional manual operation. The lift units (Fig.:5) are self adjusting and compensate length tolerances of cavity. They contact the cavity at the reference planes. Concurrent, the cell supports with adjustable spring lifters of cavity train compensate the sagging of cavity caused by its own weight and other forces.

The whole measurement procedure is accomplished by nine distance generators, two flange transmitters and two laser sensors.

The cell distance generators are aligned to the middle of each cell by an automated mechanical system. The middle locations of equator diameters are measured with high resolution potentiometric linear distance generators. A similar system with identical sensors is used to acquire the locations of centers from the 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.

In order to assure a precise measurement, the EMD has to be calibrated by a dummy cavity from time to time. (Fig.:5). It was fabricated with very low tolerances in the range of ±0.01mm. The real values of length, cell diameters and location, concentricity and perpendicularity of reference planes were surveyed by a special 3D measurement device. The deviations in the calibration are respected in the calculation algorithms used by the tuning software to enhance the accuracy of cavity measurements.

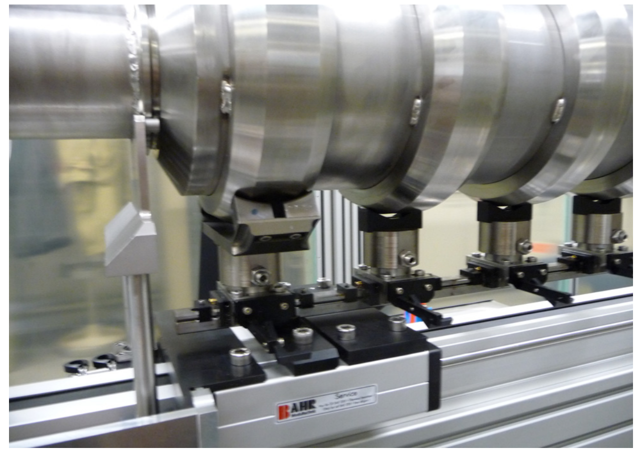

Figure 5: Lift units and CT supports with the lift units at the left, contacting the reference plane. A dummy cavity is used to calibrate the eccentricity measurement device.

In usually known measurement devices the sensors are fixed and the cavity is rotated around the beam axes on reference planes. In the realized EMD here, for the new tuning machines a measurement bar with all distance generators rotates, guided on a high precision backlash-free gear wheel, around the cavity. An additional new feature is the movement of measurement bar towards the cavity. It is driven automatically by a spline curve gear supported from high pre-stressed springs.

BEAD PULL SYSTEM

The obvious difference between normal BP-Systems and the developed one is the way the string is kept. Normally the string performs a loop. In such systems the tension of string is originated by a spring between the ends of string. Because of the string length the possible oscillation of the bead in lateral and perpendicular direction generated by the elasticity of string is very high. Besides, the sagging of string based on a length greater then 5 meters might be a problem.

To solve these difficulties and to decrease the manually effort the string is kept open. Once in the tuning procedure the string is pulled from a reservoir (Fig.:6) which at the same time tenses or retards the string to an actuator wheel on the opposite site. The very long bead movement of about 5m is translated into a short 1m vertical movement of the weight by a gear (see Fig.: 7). This guaranties also a constant string tension.

The field flatness measurement is done several times during the tuning procedure at different cavity locations. Therefore it is necessary to know the position of the bead and also the position of the cavity to identify relative position of bead in a certain cavity cell. This acquisition is done by several step encoders of actuators and positioning systems.

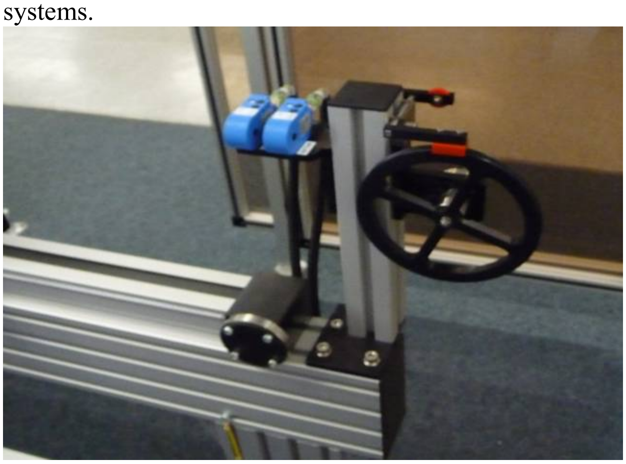

Figure 6: BPS string reservoir with sensor unit

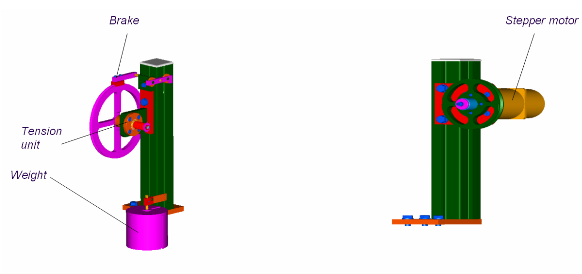

Figure 7: BPS String reservoir left and motor unit right

The initial bead position detection before the measurement starts is done by a system of two inductive sensors, able to detect the very small stainless steel bead (Tube: 0.2mm dia. /10mm length).

CAVITY ALIGNMENT TOOL

Beyond field flatness and concentricity the length and perpendicularity of cavity is a major item for cavity string assembly and thus for cavity tuning.

For series cavity tuning machines a tool to observe the cavity straightness during the tuning procedure of a single cell is needed. In our case a laser beam is sent from short side beam tube flange to a mirror mounted at long side beam tube flange of cavity. Both, mirror and laser are easily to adjust during the installation to cavity. The reflected laser beam is sent to an elliptical target fixed to a 45° notched tube, comparable to a periscope (Fig.8). The target is evaluated by a small industrial camera system.

Through digital image processing and a calculation algorithm additional deforming distances of single vice units are calculated and the tuning process is concurrently observed.

SAEFTEY CONCEPT

Because the cavity vendors will be supplied with the tuning machines by DESY the machines have to comply with essential health and safety requirements and have to be designed, built and documented in accordance to the Machinery Directive 2006/42/EC of the European Community (EC). The so called "conformity assessment procedures" are mainly consisting of the execution and documentation of risk assessment, creating a user manual and declaration of "CE conformity" formally. (CE = Conformité Européenne). At the end of the procedure each machine gets a unique serial number and can be "CE certified" by marking it with the official label.

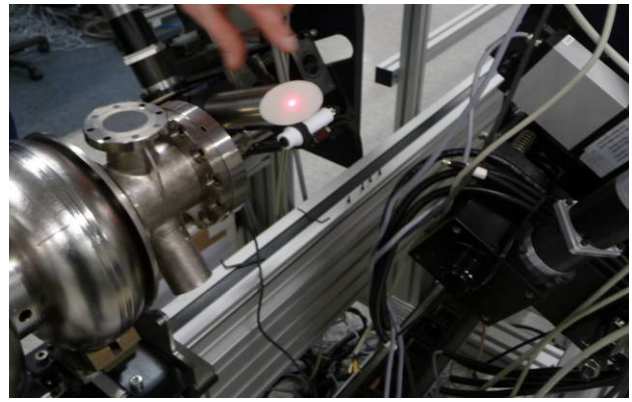

Figure 8: Cavity Alignment Tool, laser spot on target.

SUMMARY

Despite the large number of new requirements to mechanical design, electronic architecture, software framework and safety reasons an efficient series of new tuning machines was successfully developed in a collaboration between FNAL, KEK and DESY.

The testing and commissioning period of machines is in progress. With the cavity series production start of 800 cavities for the European XFEL in spring 2010 the machines will have to demonstrate their capability.

ACKNOWLEDGEMENT

We acknowledge all involved FNAL and DESY colleagues for their technical support as well as the good cooperation with the external service provider:

- Company "ZSI Zertz + Scheid", Germany, Gummersbach
- Company CE-CON Germany, Bremen (Conformity assessment procedure according to Machinery Directive 2006/42/EC)

REFERENCES

[1] F. Richard, J.R. Schneider, D. Trines, A. Wagner, "TESLA, The Superconducting Electron-Positron Linear Collider with an Integrated X-Ray Laser Laboratory: Technical Design Report", DESY 1995-2001, March 2001, ISBN 3-935702-00-0 (Complete Edition)

[2] The Free Electron Laser in Hamburg, DESY, 2007

[3] Ed. M. Altarelli et al, "The Technical Design Report of the European XFEL" DESY 2006-097, July 2007 ISBN 978-3-935702-17-1

[4] Sekutowicz J., Chen Yinghua, Wey Yixiang,"A Different Tuning Method for Accelerating Cavities", Workshop on RF Superconductivity. KEK, Tsukuba, 1989, p.849-857