# A HIGHLY CONFIGURABLE AND SCRIPTABLE SOFTWARE SYSTEM FOR FULLY AUTOMATED TUNING OF ACCELERATOR CAVITIES *

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*Abstract*

A software system has been developed to automate cavity tuning machines as part of a multi-laboratory collaboration. The system is based on a plugin framework containing a configurable set of components. Each component runs asynchronously and uses a framework for message based communication. Components run in either manual or automatic mode. In automatic mode, the system interprets a user-selected control script which executes a sequence of measurements, model calculations and tuning operations. A tuning script iterates until the prescribed tuning criteria are satisfied, or until aborted or paused by the user. In manual mode, the user controls the tuning process, deciding when and which component to run, and when tuning is complete. The software framework incorporates the blackboard architecture for sharing data and results between the various plugins. The results of the measurements and tuning are persisted in an XML-based data store, and components exist that retrieve and visualize the data. The software system is portable (Linux, Windows) and has been successfully deployed and used by Fermilab, DESY, and KEK.

## INTRODUCTION

The Cavity Tuning Machine (CTM) is a result of collaborative efforts among DESY, KEK and Fermilab [1] [2], with the Fermilab team responsible for developing system electronics and software [3]. The goal for the project was to automate tuning of accelerator cavities with the intention to support high-throughput cavity fabrication for construction of large SRF-based projects.

The tuning process includes a sequence of measurements and model-based calculations to determine the required tuning parameters, followed by the actual tuning. This process is iterative and is continued until the π-mode frequency and field flatness as well as the cavity mechanical alignment are all within the required tolerances. Automating the tuning process shortens the time required to tune the cavity and ensures the repeatability and predictability of this process. In addition, trained operators can replace RF experts at performing cavity tuning.

The main building blocks of the CTM apparatus include the base frame with a positioning system that moves the cavity between various positions, the eccentricity measurement device to measure the shape of the cavity, the gate with actuators for tuning (mechanically deforming) the cavity cells, the bead-pull measurement system, the laser-based alignment setup, and various electronic components, such as motion controls, interlocks, a network analyser, DAQ boards, and a weather station [3].

Figure 1: The cavity tuning machine.

## ARCHITECTURE

The software architecture of the CTM system is based on the concept of plug-ins, a solution built on the ability to dynamically load and execute specified components. The framework consists of a shell module and a set of plug-ins (see Fig. 2). The shell implements a queued state machine and provides the overall system control logic, data saving, control of plug-ins, and user interface integration. Each plug-in implements a separate measurement (e.g., eccentricity, field flatness) or functionality (e.g., positioning, model, assessment) and constitutes a complete module with its own user interface, logic and DAQ. A plug-in's front panel is integrated into the overall user interface. Plug-ins communicate via message queues.

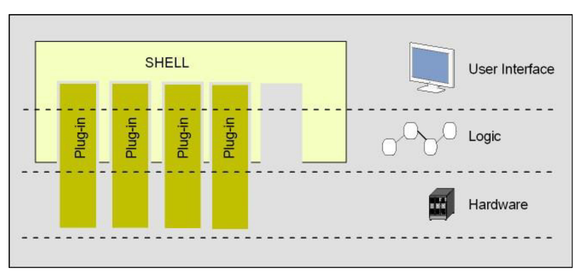


Figure 2: Plug-in architecture.

The system can operate in two modes: *manual* where the operator can use the controls available from the plug-in's front panel and *automatic* where the plug-in's front panel is disabled and the system controls the execution of plug-ins according to the logic specified in the script.

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This design, based on loosely coupled components, allows for separation of concerns and encapsulation and, therefore permits concurrent development of highly independent modules corresponding to the major measurements and functionalities defined in the system. The CTM framework utilizes a blackboard architectural model for implementing exchange of data between components, which aids in integrating the specialized modules and implementing diverse control strategies. Although functionally independent, plug-ins rely on a set of shared modules to uniformly implement common aspects such as logging, error handling, configuration and calibration data access, and data saving. Hardware access is also organized by a set of shared modules implementing logical devices.

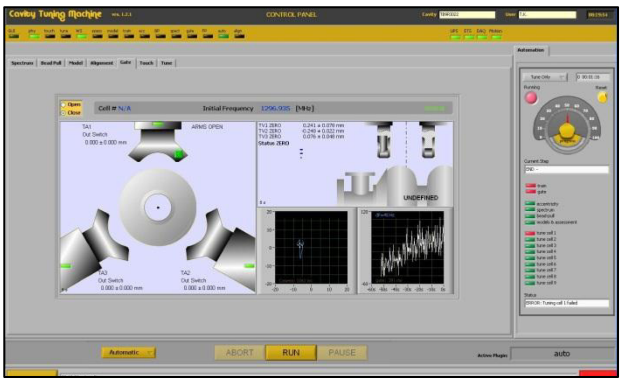


Figure 3: A plug-in executing in the automatic mode.

## COMPONENTS

The CTM system has a number of plug-in components implementing its functionality. Each plug-in is designed as a state machine that executes a series of steps. This execution may be terminated (aborted) or temporarily paused. The user interfaces for each of the plug-in components are displayed inside a panel provided by the shell (see Fig. 3). The plug-ins' functionalities are as follows:

- The **train** plug-in is responsible for transporting the cavity along the base frame of the apparatus. It can move between predefined positions and also automatically position each cell inside the gate for tuning. When controlled manually it can move to any requested predefined position or move until stopped.
- The **eccentricity** plug-in performs calibration and measurement of cavity alignment by measuring the concentricity of individual cells to the cavity axis, the length of the cavity and the perpendicularity of its reference planes.
- The **spectrum** plug-in uses the network analyser to find all mode frequencies including the $\pi$-mode frequency.
- The **bead-pull** plug-in performs a field flatness measurement using a small metal bead that is moved along the cavity axis to perturb the electrical field. This perturbation results in a frequency shift measured by the network analyser. The component implements three variations of this measurement.
- The **tuning model** plug-in determines the change in the cell frequencies required to bring the $\pi$-mode frequency to the required target value with acceptable field flatness. This module has two models to be used depending on this how far the cavity is from being in tune.
- The **eccentricity model** plug-in calculates the differential deformation of the cavity cell walls required to straighten the cavity, and the expected deflection of the alignment laser as each cell is deformed. In addition, this plug-in examines the cell frequency changes required to tune the cavity, and calculates the amount by which the cells should be pre-detuned, if necessary.
- The **assessment** plug-in compares the results of the eccentricity tuning model's calculations and determines whether the cavity is acceptable for tuning or is already adequately tuned.
- The **alignment** monitoring plug-in tracks the cavity alignment using a laser and a camera attached at one end of the cavity, and a mirror at the opposite end. The camera detects the reflected laser beam spot and when the cavity bends, the laser spot shifts its position. This position is used by the machine to control and correct cavity alignment by moving the laser spot to the calculated desired position.
- The **gate** plug-in controls the tuning arms and jaws when closing and opening the cavity cells while following the pre-defined trajectory of movements. While operating arms and jaws, this component monitors both the frequency from the network analyser and the laser spot location.
- The **tuning** plug-in controls the three tuning jaws that squeeze or stretch the cavity cell according to the tuning plan calculated by the model plug-ins. During tuning both the alignment (laser spot position) and the frequency are monitored. The process is iterative and includes a sequence of adjustments followed by frequency measurements and continues until the resulting frequency is within an acceptance range.
- The **weather station** plug-in continuously acquires and records temperature, humidity and atmospheric pressure.
- The **automation** plug-in allows the user to run the automation scripts. Each script interacts with other plug-ins and performs a desired sequence of operations.
- The **interlock** plug-in ensures the safe operation of the machine. It enables the operator and scripts to examine and reset machine interlocks and prevents human access when the machine is in operation. It also monitors the internal statuses of various




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machine elements such as the motor controller, the UPS, instrumentation rack temperature, and the emergency trip system.

## SCRIPTING

The automation plug-in executes automation scripts, which can perform all the measurements as well as cavity tuning, or just some select functionality such as calibration, cavity mounting or fine tuning. Users can supply their own scripts to further extend or customize the functionality of the machine. As with any other plug-in, the execution of a script can be suspended or aborted.

Automation scripts are sequences of instructions interpreted by the automation plug-in. The system uses a dedicated scripting language having 44 different instructions, which allow for communicating with plug-ins, controlling plug-in execution, controlling script flow, calling parameterized subroutines, handling exceptions, prompting the operator and accepting his responses, event logging and data saving, testing and resetting interlock status, manipulating indicators, obtaining the locality of the system, controlling tuning, switching between user interface panels, and sounding alert signals. In addition, automation scripts may have common sections which can be included inside several scripts, such as a set of subroutines that can be invoked from several scripts.

## DATA HANDLING

The CTM software saves diverse data from all stages of the tuning process in files using the standardized XML format. This allows the use of a hierarchical structure for the output data and promotes self-describing data, where one can identify the values, names, and types of the data from the tags that describe them.

Each cavity has its own data file. Inside that file a sequence of sections represents the full history of measuring, evaluating and tuning of that cavity. The sections are chronologically ordered and represent outputs of various components. Each section is written immediately after the plug-in completes its action, thus allowing for restarting and continuation of an interrupted tuning process.

Since XML is a language used to represent data, and as such is not especially suited for human interpretation, a set of XSL transformations has been developed to aid in presenting cavity measurement and tuning results in a human-oriented form.

## HARDWARE DEBUGGING

A separate program has been developed to facilitate testing, calibrating and adjusting hardware as well as debugging mechanical and electrical problems. It allows manual activation of all motors, and access and control of all connected instruments and peripherals, such as network analyser, weather station, DAQ boards or camera-based laser position system. Similar to the main tuning program, the maintenance program is configurable and can be extended by adding more test modules.

## CONFIGURATION

The CTM system is highly configurable. A configuration consists of a list of components to be included in the system together with a set of their properties stored in an XML file. Each section of the file describes a set of parameters for a different plug-in component, such as eccentricity, bead-pull, train, arms, or jaws. A special program has been developed for examination and modification of these parameters. The program is extensible, and new sections can be easily added to support new plug-in components.

## SUMMARY

The CTM system, a result of international collaborative efforts, has been successfully commissioned at DESY, Fermilab and KEK. Experience shows that the system has delivered on the promise to automate and shorten the tuning time of cavities.

The software developed to control and automate those machines is based on a plug-in architecture with loosely coupled components. The system is very modular, extensible and fully configurable. The blackboard-based design allows for integrating diverse specialized components and implementing various control strategies. The system's functionality can be extended or modified via scripting.

Data management, including measurement and tuning results as well as configurations and calibrations, is uniformly based on XML data format.

The system has been developed with a strong emphasis on operational safety and EU certification. It also has provisions for localization, with different behaviours specified for different laboratories. The CTM software system is portable and has been deployed on both Windows and Linux platforms.

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