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# ADVANCED OST SYSTEM FOR THE SECOND-SOUND TEST OF FULLY DRESSED CAVITIES

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*Abstract*

Cavities which exhibit a low field quench are normally discarded from usage in accelerator projects. However, they can be repaired if the exact location of the quench is known. Optical inspection alone cannot reliably locate the source of a quench. Methods that directly measure the quench, such as thermometry or second sound detection, could so far only be performed at undressed cavities. A new, specially designed, second-sound system for the first time allows the localization of the quench in multicell cavities equipped with a helium vessel. It can be easily installed in the helium pipe of the cavity. Information on the quench location can be acquired during a standard rf test. A new algorithm localizes the quench based on the real path of the second-sound wave around the cavity surface, rather than using simple triangulation. The implemented pathfinding method leads to a high precision and high accuracy of the quench location. This was verified by testing standard dressed 9-cell XFEL cavities. The system can be easily applied to other cavity shapes and sizes.

## DETECTORS

In the setup second sound oscillations are detected by oscillating superliquid transducers (OST) [1, 2]. Within the OST the electrical capacity changes due to oscillation of the ratio of the fractions of helium phases.

While the OST is biased, its capacitance changes leads to voltage changes on the measuring resistors. The voltage oscillations on this resistor can be easily measured after the amplification.

### *Single OST*

Positioning OSTs around the cavity leads to the highest resolution and lowest uncertainties of the measurement results.

OSTs of the original [2] design with a porous membrane (see Fig. 1) are often suitable for second sound tests of naked cavities. While providing a high signal level, the relatively large area of the membrane doesn't allow positioning the OST in small volumes such as a helium tank or a helium nozzle pipe. At the same time reducing of the OST dimensions reduces the signal and requires a higher gain of the amplifier.

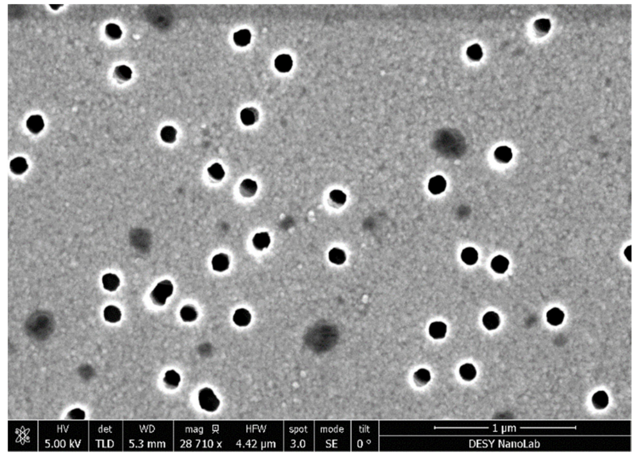

Figure 1: SEM image of the OST membrane [3].

A single OST with outer diameter of only 9 mm was developed to counter these challenges. It has an SMC connector significantly smaller than previously used SMA connector. The optional outer thread allows easy and rigid installation of such a sensor similar to a usual screw. Such sensors are used for example for horizontal test of bERLinPro booster cavities. As these cavities will be tested in HoBiCat only once, there is no need for a special holder which can provide repeated use. Therefore, four of such OSTs were installed on a plastic 3D printed holder (see Fig. 2) and positioned in a helium pipe (see Fig. 3). The holder provides precise and stable positioning of the OSTs which is important to exactly locate the quench. OSTs are connected by coaxial cables via vacuum feedthrough located on a helium pipe.


Figure 2: Four OSTs are assembled on a single plastic holder.

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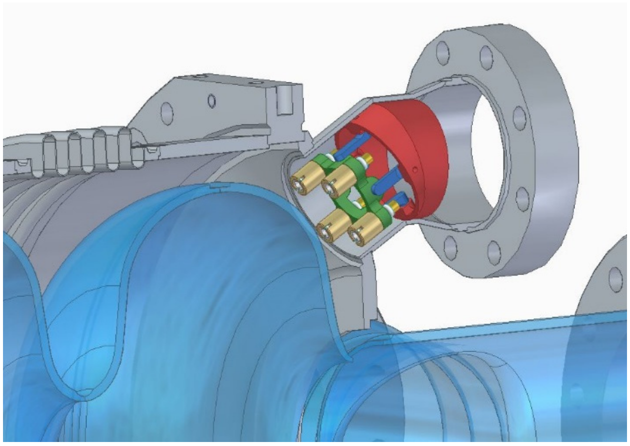

Figure 3: The OST assembly installed in a helium pipe of bERLinPro booster cavity. Cables are not shown.

### *Multi-OST*

Several OSTs can be combined in a single Multi-OST device (see Fig. 4). Such a Multi-OST can be positioned e.g. in a helium pipe of the dressed cavity to localize a quench position. Multi-OST of various dimensions and with different numbers of detectors (up to 8) were produced for different cases.

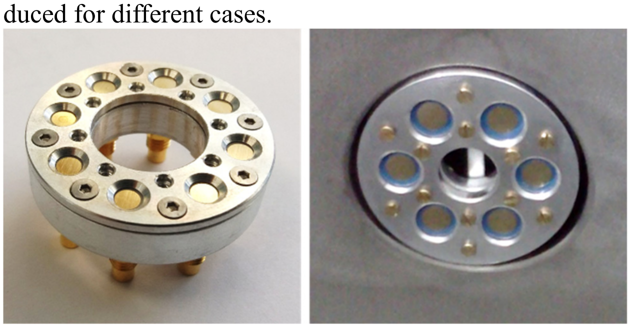

Figure 4: Multi-OST with outer diameter of 38 mm and 8 detectors (left) and with outer diameter of 52 mm and 6 detectors installed in the nozzle tank tube of the dummy helium vessel.

### *Retractable Holder for Dressed Cavities*

A special retractable holder was designed for easy and fast installation of the multi-OST in to the helium pipe of a standard 1.3 GHz E-XFEL cavity. The entire mounting system is placed inside a cylindrical cartridge (see Fig. 5). The cartridge is installed in a two-phase helium pipe during preparation for the vertical test of the cavity. The multi-OST detector is placed in position by turning the knob on top of the cartridge. The whole installation can be done in 2-3 minutes without additional tools. The setup is designed to be repeatedly used and provides precise positioning of the sensor. It also does not require any additional cavity preparations.

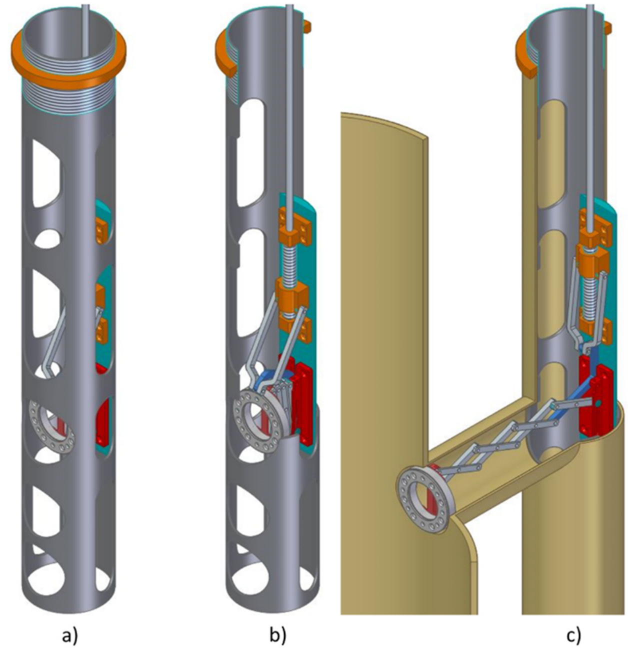


Figure 5: General view (a), section view in a mounting state (b) and in retracted state within cavity helium pipes (c) of a second-sound measurement system for standard E-XFEL cavities. Top plate of the cartridge is not shown.

## AMPLIFIER

A reliable and precise detection of the second-sound wave is the most important part of the second-sound test. Low noise and high temporal resolution of the signal are necessary for accurate localisation of the quench origin.

As was shown in [3], the amplifier requires stable power supply and proper signal shielding to provide a high signal-to-noise ratio.

A new amplifier was designed. It consists of two main parts: a power supply and an amplifier located on separate PCBs connected by coaxial lines. So no noise occurs in the amplifier circuit due to interference (see Fig. 6).

The power supply provides three power lines: +18 V and -18 V for operational amplifiers (op-amps) and +96 V of polarizing voltage. It requires 24±1 V as input voltage and is powered by a conventional 240 V AC adapter. Power filtering is performed on the amplifier board side: the polarizing voltage is reduced to low-noise +90 V; +18 V and -18 V are reduced to low-noise +15 V and -15 V using low-dropout regulator. Op-amp voltage can be reduced depending on the analog-to-digital converter being used for readout. A single power supply can provide power to several amplifier boards.

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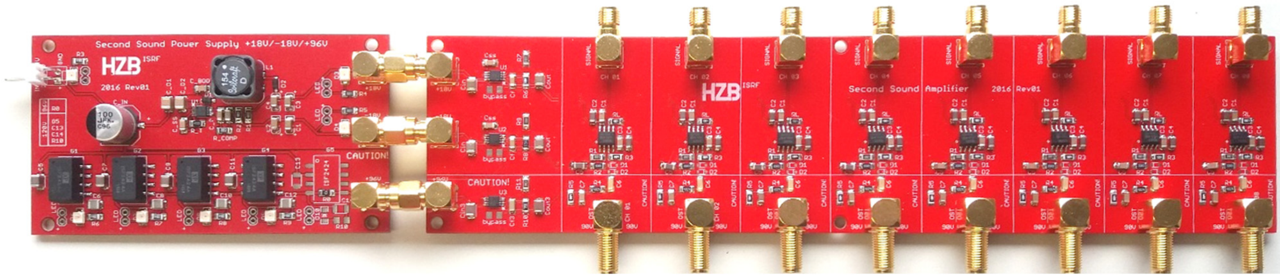


Figure 6: Three-channel power supply (left) and a low-noise 8-channel amplifier (right). The power buses are connected by coaxial lines to reduce interference.

The amplifier shown in Fig. 6 has 8 channels. Each channel has gain of 100, however it can be changed in case specific OSTs are used. A typical noise level of the output signal with OST connected is ±5 mV, while the signal level depends on the OST type and its area and is in the order of 1 V or higher. In addition, a high pass filter is optionally used in the op-amp biasing circuit. For example, a high frequency noise of 300 Hz presents in a helium cryostat because of the pumps and is filtered out by such approach. A typical OST signal acquired with the amplifier is shown in Fig. 7.

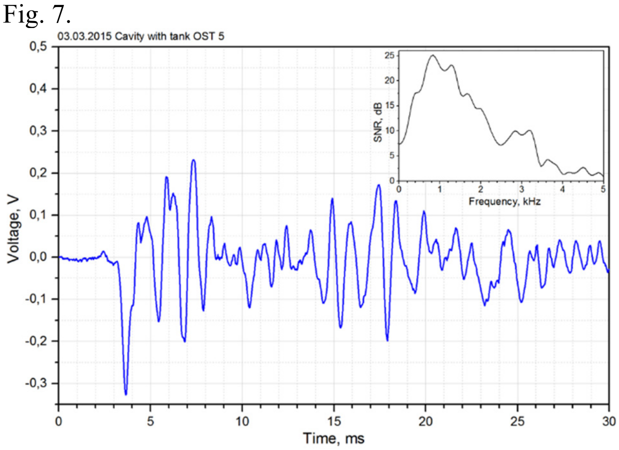


Figure 7: Typical OST signal. Insert: power spectrum of the signal relative to the noise level. A high pass filter is used to remove the noise at 300 Hz.

A second-sound amplifier is a reliable device which provides low-noise OST signals and can be connected to a wall-plug without additional requirements. Current to OST is limited and no danger or malfunctions occur in case of short-cut in OSTs or cables.

## ALGORITHM

To localise the quench, the algorithm uses the cavity shape, positions of the OSTs and the OST detection time (see Fig. 8) derived from the second-sound measurements.

Using the simulation of the cavity geometry the algorithm finds the shortest path between the OST and any point on the cavity surface, even if it is not in the direct line of sight of the OST. In the general case, such a path is a

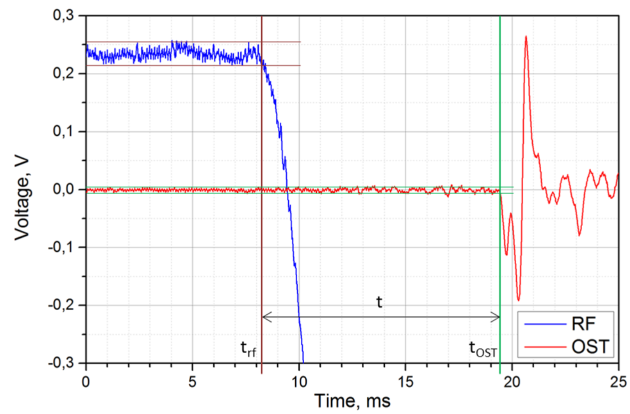


Figure 8: The OST (red) and rf reflected (blue) signals. Noise levels are shown by the horizontal lines. The rf-detected quench time $t_{rf}$ and the OST signal edge $t_{OST}$ are shown by the vertical lines.

combination of direct rays in free space and one of several geodesics (shortest path between two points) on the cavity surface. As only the shortest path is used, there is no need to calculate any reflections. However some effects, such as the finite size of the OST and stiffening rings with holes must be accounted for [3].

The calculation is computationally intensive depending on the desired accuracy. The most intensive calculations relate to building the graph based on the cavity shape and are independent of the second-sound measurements. Such calculations are separated (see block 1 in Fig. 9) and the result is calculated only once (for the cavity shape used see Fig. 10) and is stored in the form of the graph.

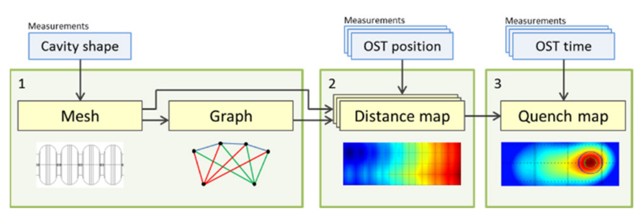


Figure 9: A diagram of the full algorithm used for the second-sound analysis [3].

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The mesh and the graph can be calculated by different techniques with the desired precision. Significantly less time-consuming calculations of the distance maps are based on the graph (block 2 in Fig. 9). Such calculations should be done for the specific OST positions. If the same OST positions are used for different tests, the same distance maps can be used. Calculation of the quench map can be done "on-the-fly" during the cavity test, as no specific software or additional cavity-shape information is required (block 3 in Fig. 9).

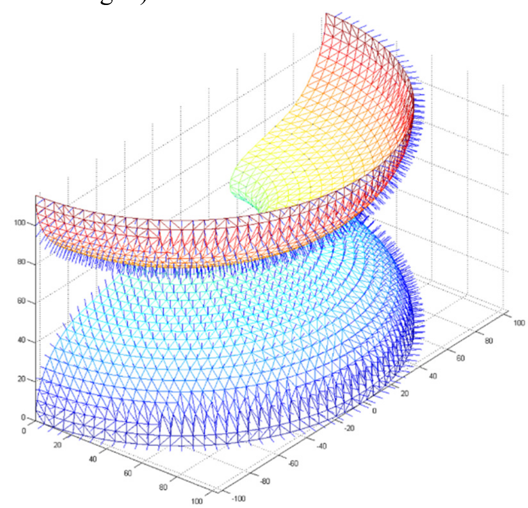

Figure 10: Half of the dumbbell shape with normals and triangular mesh used for 9-cell 1.3 GHz TESLA-shape cavity [4].

Quench map and Distance maps are stored in the form of 2D matrices and can be interpreted as images (see Fig. 11). This allows easier visualisation of the quench area.

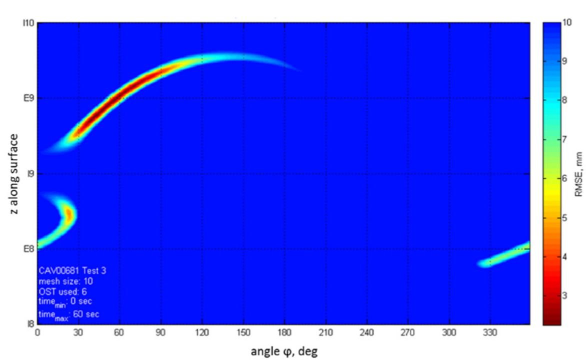


Figure 11: A part of the quench map for the dressed cavity.

This algorithm was verified by second-sound tests of several naked cavities (without the helium vessel) with several single OSTs placed around and cross-checked by temperature mapping. In those tests the uncertainty was below 10 mm (see Fig. 12).

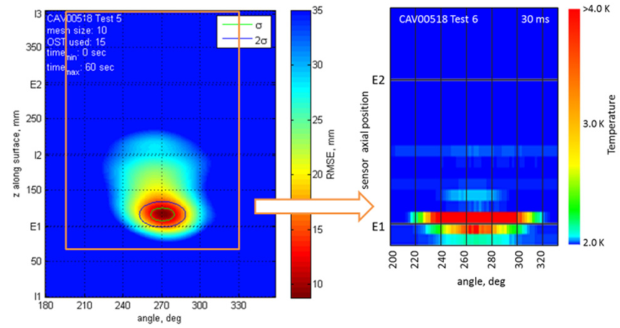


Figure 12: Part of the quench map (left) and the temperature mapping data for the same area of the cavity surface 30 ms after the rf quench (right) [3].

The algorithm also accounts for a fast heat propagation in Nb which results in a shorter detection time. In Fig. 13 the evolution of the hot area derived by temperature mapping is shown. Lines show the 50mK isotherms for the time interval 1-12 ms in steps of 2 ms after the time of 2 ms. Time is counted from the rf signal that indicates the quench. Dots show datapoints for the 12 ms contour. The z coordinate of Equator#1 has been set to 0 intentionally. The aspect ratio of the area is kept as 1:1. The positions of the temperature sensors are indicated on the right-hand axis.

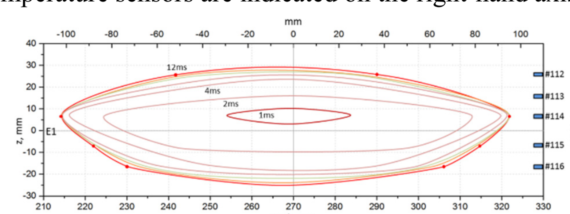


Figure 13: The evolution of the hot area derived by temperature mapping [3].

Results of the second-sound test of dressed E-XFEL cavity are described in detail in [3, 4].

## CONCLUSION

The hardware and algorithm for second-sound tests were developed and commissioned.

A new amplifier allows reliable determination of the signals edge without additional filtering.

The developed algorithm was verified by testing single and 9-cell cavities. A universal code allows for full 3D simulation of the cavity and second-sound path. The quench position localised by the algorithm was verified by the temperature-mapping system.

This system allows second sound analysis of dressed cavities. It does not require any mode measurements, which can only detect the limiting cell, hence there is no need to dismount HOM antennas, a procedure requiring a clean room.

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A retracting mounting system developed for E-XFEL cavities allows precise positioning of the sensor. The installation/dismounting process takes less than 3 min including cables connection. This ready-to-use system could be routinely used as a part of the standard vertical test during the cavity production.

This approach can be adopted for the testing of nonelliptical SRF cavities.

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