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Alternating Current Oscillation Shaper for Superconductor Research

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A power source has been developed that generates various configurations of alternating current oscillations. The source adds heat to the superconductor in small, controlled portions, which allows studying dynamic processes on alternating current with amplitudes Ia exceeding the average critical values I_c. Analysis of voltages on the sample allows recording the appearance of a narrow normal zone and determining the conditions for stable operation of the superconductor in the critical region. Using video recording, it is possible to study the process of developing thermal instability up to the burnout of the material.

Keywords: superconductivity, dynamics, alternating current.

1. Introduction

In the recent year, there's been a considerable effort to employ high-temperature superconductors (HTS) on alternating current devices, such as: power lines, current limiters, electric motors and other high-energy devices that require sustained work regimes on current amplitudes that are close, and often exceed, the superconductors's critical current I_c. To achieve this task, it is beneficial to know the dynamics of the superconductor when carrying alternating current.

Acquisition of current-voltage (I-V) characteristics from HTS tapes when entering alternating current (AC) or direct current (DC) presents certain problems, that complicate the measurement of material properties. First, the current density distribution is irregular along the length of the HTS tape [1]. Second, the index value of current growth (*n*-value) is relatively low when measuring I-V curves; the thickness of the stabilizer layer is also low. Therefore, if a normal area appears somewhere on the tape, its expansion rate is significantly slow, about 10-100 centimeters per second) [2, 3], and results in a local overheat of the superconductor. Also, it is almost impossible to predict where the normal area is going to appear. The temperature buildup at the normal area is irreversible, and usually leads to burnout severing the tape during its acceptance testing.

Traditionally, I-V curves on overcritical current are acquired in pulse mode, with pulses going at power grid frequency. With this approach, the overheating is not that high, and allows the current to significantly exceed the critical current. The shortness of the exposure to such a current was the foundation of research work that focused on the dynamics of I-V characteristics, measured by applying a quasi-impulse AC current (decaying AC) with amplitude significantly larger than critical current value I_c [4].

The purpose of this work was to create a device that generates a train of fixed-amplitude (e.g. non-decaying) half-sine AC pulses, with preconfigured number of pulses, preconfigured delay between the pulses and the ability to issue partial pulses. The device was built to research the dynamics of I-V characteristics of HTS. It presents a much needed opportunity to avoid the emergency of a local normal area that inevitably leads to damage of the superconductor.

2. Circuit diagram of the current shaper

Figure 1 shows the electric diagram of the device. It contains two main parts: the measurement circuit with stepdown transformer Tr1 and the control unit CU. The secondary coil of transformer Tr1 has internal resistance of less than 10 mΩ and outputs up to 32 V. Connected in series in the measurement circuit, there are: reference resistor R_n = 0.25 mΩ to measure the current; HTS tape sample R_s, submerged in liquid nitrogen; variable resistor R_{var} to adjust AC amplitude; and two parallel thyristors T1 and T2, facing each other (both are model T500 current-controlled tablets). This circuit can produce currents up to 500 A. The duration of the current can be as long as R_{var} resistor can withstand without overheating – up to ten seconds. To measure the current of I-V curve, Rogowski coil RC was added to the setup.

Control unit CU outputs a rectangular boxcar pulse – the control pulse. Duration of this pulse is usually set to be a multiply of AC power grid half-sines (T/2 = 10 ms). The pulse purpose is to gate the current in the measurement circuit by controlling its thyristors T1 and T2. At the falling edge of the control pulse, the measurement current will be tured off automatically, at the moment when the current in the thyristor switches direction. The control unit is a separate board. This board includes: small stepdown transformer Tr2; voltage null detector subcircuit VND; voltage sign detector subcircuit VSD; ATmega328 controller MC, model MOC3023 opto-isolator OP with triac output; model BT134-600 controlling triac TC; and a +5 V stabilized voltage source to power the microcontroller and the rest of the control unit CU.

The gate control pulse originates from ATmega controller MC and goes to opto-isolator OP, which galvanically separates the high-current measurement circuit from the mains ground. After crossing the opto-isolator, the control pulse drives controlling triac TC, which, in turn, simultaneously opens/closes both T1 and T2 thyristors, thus gating the high current in the measurement circuit.

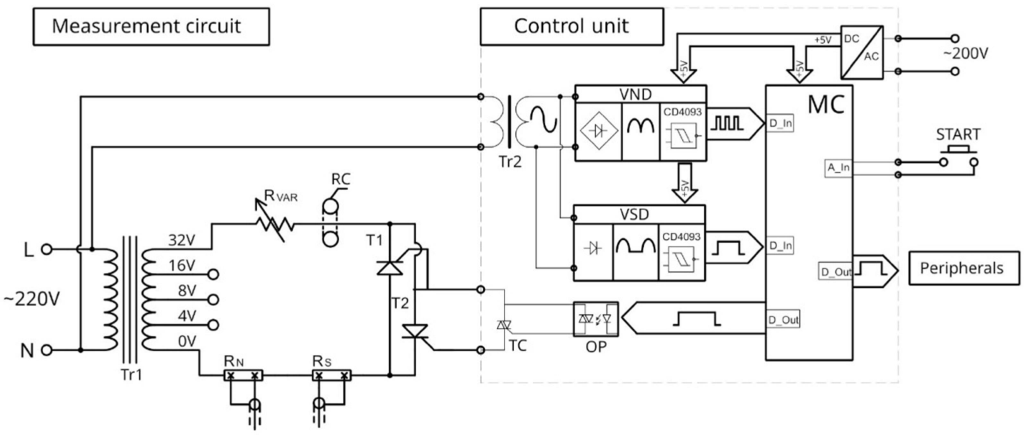

Fig. 1. Electric circuit diagram of the alternating current oscillation shaper device: transformer Tr1 powers the high-current measurement circuit with HTS tape sample R_s; reference resistance R_n; and Rogowski coil RC. The control unit CU is a separate board with microcontroller MC.

The boxcar pulse that controls the thyristors should place its leading edge where the grid voltage is zero; also, it should take in account the grid's phase to consistently start each run from the either upper/positive AC half-wave or from the lower/negative one. It works as follows: the voltage from stepdown transformer Tr2 is send to the so called voltage null detector subcircuit (VND), where it first rectified by a dioge bridge. Near each voltage zero level, a Schmitt trigger in an inverted configuration issues sharp, positive spikes at intervals synchronized to AC grid half-sine. Another subcircuit, the voltage sign detector (VSD) detects AC voltage sign. Instead of a diode bridge, it has a single diode that only passes the positive/upper part of the grid's voltage sine. Another Schmitt trigger in an inverted configuration then consumes the diode output to form a positive boxcar pulse. That pulse follows only the negative/lower part of grid's AC.

Both VND and VSD outputs are fed as digital inputs to ATmega controller MC. Digital inputs are orders of magnitude faster than analog ones, so using dedicated circuitry for VND and VSD is justified. The stored program was written in cross-platform C++. It uses Arduino IDE to deploy on chip and python to unit-test on a desktop PC. The program monitors inputs from VND and VSD; it issues outputs to control the thyristors. The program also starts data acquisition, controls video camera and synchronizes the video footage to the on and off of the current in the measurement circuit.

The program waits for the start button press, then synchronises itself to the AC grid rhythm, and when ready, emits a five millisecond pulse to Bluetooth remote, wirelessly starting the video camera. A second after the camera had been activated, the stored program begins to shape the pulse train to control T1 and T2 thyristors. Thyristor control signal has the following structure: pulses from voltage sign detector (VSD) and voltage null detector (VND) hint at the moments where the program may enable the current, chip's internal clock and voltage null detector predict where the current must be disabled. The current in the sample measurement circuit is enabled at the leading edge of the control signal, shut down at the falling edge. Duration of the control pulse is usually set to be a multiply of AC half-sines ($n * T/2$, where n is integer).

Successive runs of the above-described subroutine can be chained to obtain various patterns of AC oscillations in the measurement circuit. Current can be interrupted, zero-current delays of set duration can be placed between the oscillations. Typical examples of the current patterns are shown below.

Control pulse is forwarded to the data acquisition equipment, to tell the total duration of the pulse train generated and act as a synchronization pulse, from the periphery's point of view. On Figure 1 it is labeled "Peripherals". One of these peripheral devices was a video camera. The camera has been placed over the HTS tape sample, looking down. The distance between the camera and the tape was 15 cm. The framerate was 120, enough to film the state of the sample at each AC half-sine. To sync the video footage and the acquired electrical data, a light emmitting diode (LED), controlled by the stored program, located in the camera's view. The LED blinks shortly (about 10 μs), once on the leading, once on the falling edge of the synchro / thyristor control signal. By using this optical method, two frames of the footage, marked by LED blinks, were used to synchronize video footage and oscillations of the current.

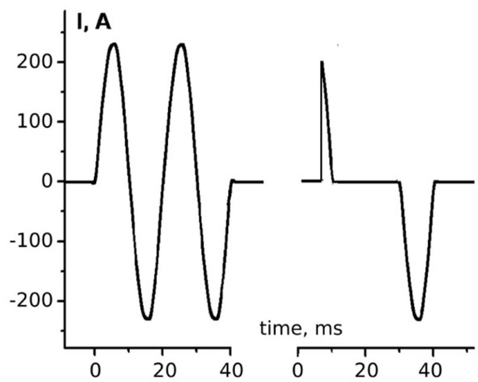

Fig. 2. Various examples of interrupted current shape in the measurement circuit.

Due to slight difference of T1 and T2 thyristor specs, the upper/positive and the lower/negative halfs of AC current have slightly different amplitudes. In our case, the amplitude difference ($\pm I_a$) had not exceeded 0.4%.

Figure 2 shows typical fragments of current oscillograms, produced by the shaper device. It can be singular half-sine oscillations, continuous segments of oscillating sine, delays can be placed between the pulses, the pulses themselves can be cropped at the leading edge to generate sharp spikes useful to control the amount of power inflicted on HTS tape.

3. Description of samples and the measurement procedure

Device features were tested by measuring the critical properties of "SuperOx" high-temperature superconductor tape. This tape is 4 mm wide and 0.05 mm thick. Its base is a 38 μm Hastelloy substrate covered by buffer layer, covered by 2 μm superconductive yttrium barium copper oxide (YBCO) layer. This particular tape has thin stabilizer layers, about 5 μm of silver and copper on each side.

In the experimental setup, a 150 mm long tape piece had been soldered to two free-hanging copper leads. Tape's longitudinal axis was horizontal, the tape surface was parallel to the vertical plane. Resulting fixture was submerged in liquid nitrogen. Vertical placement of the tape's planar surface provided equal cooling conditions to the both sides of the tape. Areas of the tape, soldered to the current leads, were about ≈ 15 mm long each. Potential measurement wires were soldered distant apart to get $L \approx 100$ mm of tape between them. Such long length of the measured tape segment was dictated by necessity – oscilloscope resolution isn't high enough (about two orders of magnitude worse than DC nano-voltmeters have). Measure wire contact points spaced wide enough allowed to get close to the critical electrical fields, commonly used in direct current I-V curve measurement.

Electrical measurements were conducted by digital oscilloscope AKIP-4131/1A. Synchro signal from control unit CU was on Channel 1, its leading edge synchronized to the current-enable signal going to the thyristor gate. The voltage drop $U_s^*(t)$ from the HTS sample was on Channel 2. Rogowski coil voltage U_{rog} was on Channel 3.

Non-insulated oscilloscope feeds get distorted when two channels simultaneously measure voltage drops at two resistors connected in series (in our case, R_n and R_s in the measurement circuit). That was the reason why Rogowski coil was used to get the current readings. The coil was pre-calibrated against the reference resistor R_n voltage. Rogowski coil voltage, integrated, presented as the current oscillogram at Channel 3.

The measurement procedure was simple: keep increasing the number of AC half-sines, measure the voltage, compare to the previous experimental run. To remove magnetic field inductive noise from the signal of the current carried by HTS tape sample, two methods were employed. First method consisted of measuring the HTS tape sample voltage $U_{S0}(t)$ at current amplitude not exceeding the critical current, $I_{A0} < I_c$. The signal from the superconducting sample is zero in that case. Since noise is proportional to the current, it can be subtracted from the measured voltage U_s^* to get the signal of the HTS tape itself.

$$U_s(t) = U_s^*(t) - U_{S0}(t) \cdot \frac{I_a}{I_{A0}}. \tag{1}$$

In the second method of removing the noise, the signal from Rogowski coil, proportional to the inductive noise, was downscaled 9 times and then subtracted from the voltage signal $U_s^*(t)$.

At moment when the voltages $U_s(t) > 0$ begin to show, it is easy to estimate the value of critical current. Using two half-sines shifted by time, it is possible to see how the critical evolve during the delay. This way, the characteristic time of thermal relaxation can also be estimated [4].

4. Measurement results

At liquid nitrogen temperature T = 77 K, various pieces of HTS tape had their critical current previously measured: I_c = 176 A (± 3 A). By gradually increasing the number of current oscillation from one 1 to 10 sine periods, the dependence of max voltage amplitude on pulse train length, $U_s^*(t)$, was collected. Figure 3 shows the dependence of $|U_s^*(t)|$ maximums at current amplitude I_a = 220 A. As can be seen, U_s has a saturation trend, and the saturation happens when the heating of the superconductor is compensated by heat dissipation/removal.

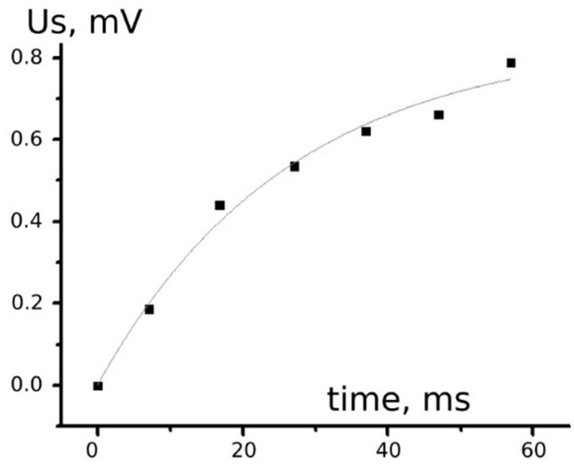

Fig. 3. Dependence of voltage maximums $|U_s^*(t)|$ at I_a = 220 A.

Figure 4 shows a fragment of $U_s^*(t)$ dependence at current amplitude I_a = 220 A and total oscillations length of 2 seconds. For illustrative purposes, the data on this figure still contains the inductive noise.

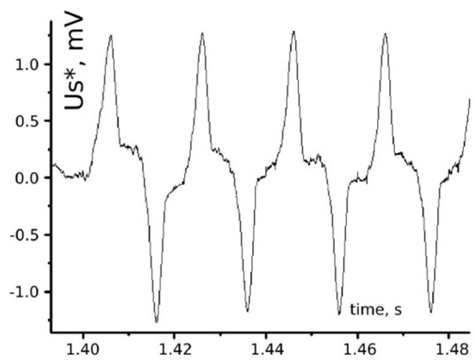

Fig. 4. A fragment of voltage dependence $U_s^*(t)$ when the HTS tape is at I_a = 220 A current amplitude (inductive noise not removed).

The constancy of U_s^* presents the stationary current carrying regime, when the boiling of liquid nitrogen compensates for the heating of the superconductor briefly being in the resistant state. In that particular case, the current amplitude I_a was exceeded the critical current I_c by 45 A, but it was still acceptable.

Increase of the current amplitude to 245 A resulted in a radical change of $U_s(t)$ behaviour. Figure 5 shows dependence $U_s(t)$ (this time, without inductive noise) at current amplitude I_a = 245 A. As can be seen, U_s grows with a positive curvature $(d^2U_s / dt^2 > 0)$. The framed insert in Figure 5 shows U_s dependency being critical with increased plot scale. Up to 4th period (0.08 s) one can observe spans of zero derivative $dU_s / dt = 0$ near the sign changes, the evidence of superconductive state at these intervals of time.

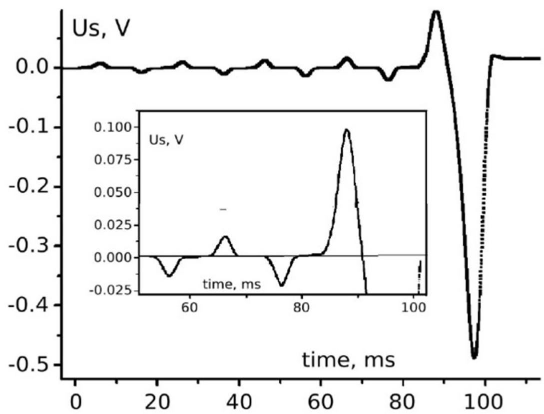

Fig. 5. Sample voltage at I_a = 245 A, during five periods of AC.

It worth to be noted, that while the pulse train consisted of less than 4 periods of AC sine, the nitrogen boiling has been observed, distributed regularly along the entire length of HTS tape. When the pulse train was increased to 5 periods (0.1 s), the voltage at the last half-period reached 0.5 V, as can be seen on Figure 5. Since at t = 90 ms zero derivative $dU_s/dt = 0$ is no longer there, this indicates that some part of the sample undergo a transition to normal state. A local, but intense boiling of nitrogen was observed at the time, followed by sharp audible "pop". Seems like the "pop" occurs due to cavitation, when the nitrogen boiling regime changes from bubbles to film.

Superconductivity had ceased when the voltage reached ≈ 0.1 V. At current amplitude I_a = 245 A, it corresponds to resistance $r = 0.41$ mΩ. Before the experiment, the thermal dependency of the resistance was measured for tape piece of L = 10 cm. At room temperature, its resistance was $R_{300} = 40$ mΩ, further reducing linearly up to $R_{100} = 12.5$ mΩ at T = 100 K. Low resistance, observed at Figure 4 indicates that only a short part of HTS tape became normal. Its length, x_n, can be estimated from the fraction of resistance r and the resistance of the entire tape between the potential measure contacts, at the critical temperature T = 100 K.

$$x_n = \frac{r \cdot L}{R_{100}} = \frac{0.41 \cdot 10}{12.5} \approx 0.3 \text{ mm.} \tag{2}$$

This estimate tells that the size of the local normal area does not exceeds several millimeters. The HTS tape then has been re-heated and no visual changes were found on it.

The tape has been cooled again. The length of the pulse train been increased up to 10 periods of sine. Resulting voltage rose up to 20 V, sharply, and then the current was severed by the oscillation shaper device. A bright flash of light occured at the location of the normal area. Stills from the video footage and comments follows.

Figure 6 shows how the voltage amplitude at the sample (max $|U_s^*|$) grew over time up to the moment of turning off the current at I_a = 245 A. The figure inserts contains the fragments of the oscillations of U_s, for the beginning and for the end of the pulse train. It is seen, that after t = 0.08 s oscillations undergo a radical change. Superconductivity is no longer present, and each oscillation period brings a sharp increase of the derivative dU_s^* / dt, at the every change on the voltage sign. Since the current amplitude is constant, it indicates a localized resistance rise. Note, that at the very end of the pulse train the voltage U_s^* turned zero right at the moment the oscillation shaper severed the current. Should the tape been burn between the measurement contacts with the input current still on, the measurement circuit would continue to register the oscillating voltage U_s^*, going from Tr1 transformer output coil.

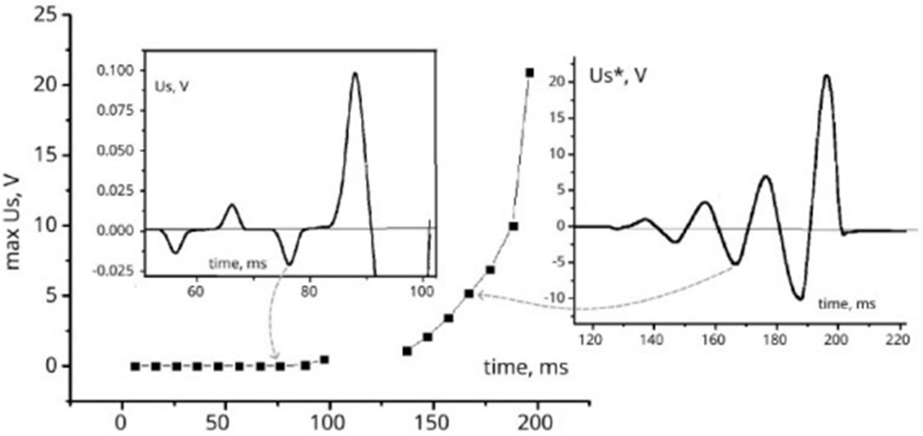

Fig. 6. Voltage amplitude dependency U_s^* for ten periods long pulse train at current amplitude I_a=245 A. The insert shows voltage from Figure 4, for comparison.

Emergence of a narrow resistive zone brings a radical change to the dynamics of the superconductor and prevents from using models, for example, [5]. That model assumes the resistive state not being narrow, but evenly distributed along the full length of the tape piece.

To the obvious conclusion of the experiment: in the presence of AC currents, sustained superconductive state is only viable if the voltage amplitude U_s remains constant over time. In other words, emergence of a normal resistive zone should be avoided for a safe and non-destructive I-V characteristic measurement. The voltage derivative dU_s/dt should also be kept low.

A curcuit-controlled video camera provided an opportunity to look at the emerging thermal instability: there is a localized nitrogen boiling at the formation of a normal zone, then temperature reaches high, and the tape material begins to fragment and evaporate into the surrounding liquid nitrogen vapour. Figure 7 shows five stills from the footage. The time is shown on the frames. On 0th still the time is also 0, the source of overheating forms there, visible as red dots. Then two bright flashes appears. Their intensity is maxed on still 3. On the following still the current had been turned off, so all the succeeding stills displays fading brightness of the flash. Last still (91 ms) displays chaotic bright dots, they disappearsed at 373th microsecond, if counted from 0th still.

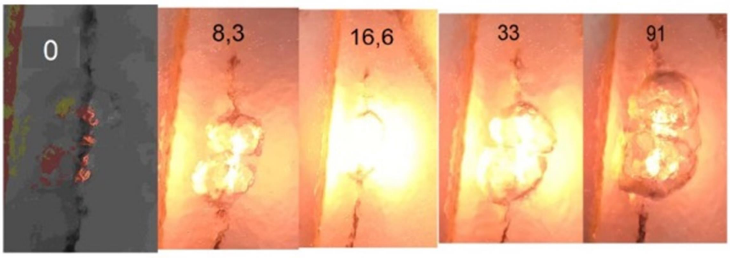

Fig. 7. Stills from the video when the tape been carrying AC current of amplitude I_a = 245 A. Numbers on every still are milliseconds from the first signs of ablation.

Figure 8 shows a piece of tape after re-heating. Its metal had evaporated in two areas. The second isthmus is narrower. Both isthmuses remain, thanks to the current disconnection promptly performed by the current shaper device. Edges of the metallic parts are relatively crisp and followed by dark stripes. Most probably, it is YBCO and buffer layers. Then goes the reddish layer of copper. At the edges of the damage, the copper had recrystallized and developed a granular structure. 3 mm to 4 mm beyond the damaged area the tape remains smooth, as it originally was before the experiment.

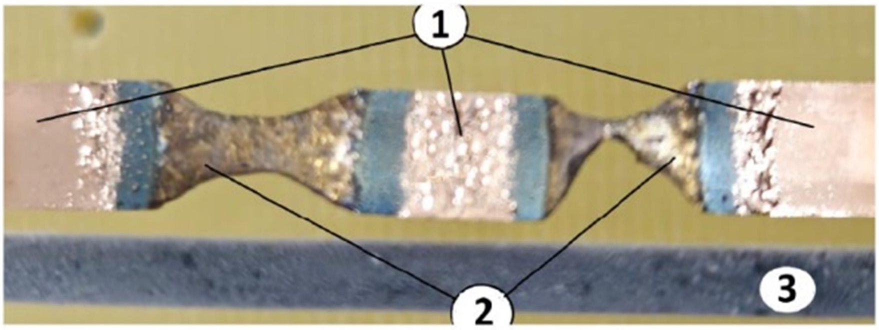

Fig. 8. Photo of the tape after the parital ablation. 1 – copper stabilizer, 2 – Hastelloy substrate, 3 – U_s^* voltage measuriung cable (diameter 2 mm).

Any increase of input current will result in these events unfolding earlier. In our case, the amplitude of input current I_a = 265 A resulted in a normal zone emergence at the second half-period of AC sine. Voltage amplitude U_s had been rising up until the 4th period, and the following period resulted in a burnout.

5. Conclusion

Intended purpose of the proposed oscillation shaper device is to regulate AC oscillations to a set configuration. Stepwise increase of the number of oscillation on each experimental run reveal the dynamics in the superconductor on each half-period of AC sine. Analysis of the experimental data, gathered that way, allows registering emergence of the normal area before any irreversible damage inflicted on the HTS material. By independently regulating both the amplitude and the number of AC oscillations, it is possile to study the emergence of instability of the superconducting state at over-critical regimes, e.g. to deterimne how suitable is that particular superconductor for carrying AC current.

Optical registation gives an opportunity to get a better look on the emerging thermal instability progression, in liquid nitrogen, up to the material evaporation.

Declarations

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- This work was carried out within the thematic plan of NRC "Kurchatov Institute".

\end{itemize}

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