Limitations on the Use of Acoustic Sensors in RF Breakdown Localization

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Abstract

X-band accelerator structures, meeting the Next Linear Collider (NLC) design requirements, have been found to suffer damage due to radio frequency (RF) breakdown when processed to high gradients [1]. Improved understanding of these breakdown events is desirable for the development of structure designs, fabrication procedures, and processing techniques that minimize structure damage. Using an array of acoustic sensors, we have been able to pinpoint the location of individual breakdown events. However, a more accurate localization is required to understand the interaction between the phonon or the sound wave with the OFE copper.

1 Introduction

As part of the R&D effort for the Next Linear Collider (NLC), the attainment of high gradients (70MV/m) with a breakdown rate below 1 per 10 hours must be demonstrated [2] [3]. In the Next Linear Collider Test Accelerator (NLCTA), at SLAC (Stanford Linear Accelerator Center), RF travelling and standing wave copper structures, designed to meet the needs of the NLC [4], are being tested.

To reach an NLC accelerating field of 70MV/m with a 400ns pulse length, megawatts of RF power are poured into the structures. Depending on the design and type of structure, this power can vary from 73MW for a 60cm long travelling wave structure with a 3% group velocity (H60Vg3) to 150MW for some structures 180cm long. Part of the RF power is transformed in the copper into heat. The lost power is up to 2/3 of the input power for a structure kept at 45°C. The thermal expansion of the copper, as the structures fill with RF power, causes sound to occur on every RF pulse. Using extremely sensitive piezoelectric microphones (acoustic sensors), it is possible to "listen" to the accelerator structure as it is running, cf Fig.1.

High gradients are obtained by exposing the structure to High Power Pulsed RF (HPP). This technique is called RF processing. During processing, the structure occasionally responds by arcing, i.e breakdown. A breakdown is characterized by a shut off of the transmitted power with up to 80% of the incident power absorbed in the arc [5]. This

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Figure 1: T53VG3RA (53cm long travelling wave structure of 3% group velocity) structure covered with acoustic sensor

extra energy is deposited in the copper, and a part of it is converted in extra phonons (heat and acoustic) that can be picked up by our acoustic sensors. With this technique, crude localization of a breakdown is straightforward, and complementary to the standard RF analysis with directional RF couplers.

Getting a precise localization of where the breakdown occurs requires a short wavelength sound wave. However, the interaction between the wave and the copper grain structure can become troublesome, hence not allowing good spatial resolution. In order to go forward on localizing breakdowns, we tried to identify the problem cause(s).

2 From RF Breakdown to Acoustic Sensor

The RF accelerating structure is subject to chemical degreasing and etching and thermal treatment, this step is the pre-processing, before it is RF tested. The use of acoustic sensors in the environment of accelerators is rather new and the way of pre-processing a structure has an impact, not only on the performance of an RF structure, but also on the understanding of the acoustic results obtained, cf §3. Despite the fact that detailing the cleaning procedure is out of the scope of this paper, it is still necessary to mention the SLAC process, as no suitable reference exists.

The NLC cleaning procedure for most of the structures built so far starts with a perchlorethylene vapor degreasing for all single OFE copper cells, followed by a chemical etching (up to 60s for poly-crystalline machined cells). The cells are assembled into structures and bonded at 1020°C in an atmosphere of hydrogen, the full structure is "wet" and "dry" hydrogen fired at 950°C. Ancillary couplers and water cooling tubes

are then brazed onto the structure. The structure is then RF tuned using a bead pull technique [6]. Finally the hydrogen is thermally desorbed by vacuum firing for two weeks at 650°C. The full structure is then installed at the NLCTA and baked at 220°C, before the beginning of an RF processing. The purpose of this extreme fabrication/processing schedule is the removal of the contaminants, gas and particles, that contribute to field emission and participate in breakdown. The in-situ bakeout, at 220°C, is now omitted. FNAL (Fermi National Laboratory) has a similar process but the structure are brazed in a 500 mTorr Ar atmosphere, and then vacuum fired [7].

There is two ways to RF process a structure, one is to slowly apply an electric field with a high enough intensity to electrostatically remove a particle from a surface. The length of the pulse has to be short enough for avoiding the fusion, by Joule heating, of the particle to the surface. The second way, used for NLC structures, is to apply a very intense electric field in order to melt the emitter, without causing damage to the accelerating structure [8] [9]. The RF processing starts with fixed pulses of 50 ns, and pedestal electric field. The electric field inside the structure is raised every minute by 1 to 2% until it reaches 70 to 75 MV/m, unless a breakdown happen. This sequence is then repeated for pulses length of 100 ns, 170 ns, 240 ns and 400 ns. If a breakdown occurs during the pulse, the RF control system shuts off for 60 s. When resuming operation the RF control system is ramps up, first with the power at a shorter pulse length and then is widening the pulse. Depending on the structure, this RF processing can take from 100 to 1000 hours.

Despite such careful pre-processing, breakdown can occur during RF processing. These breakdowns result in physical damage to the structure [1] and more troublesome, detuning, or phase shift [10]. The particle beam, electron or positron is fully accelerated at every cell of the RF structure only if the beam is at the right phase of the accelerating electrical field. The structure is designed in such a way that each cell has a geometry that insures resonance at 11.424 GHz and appropriate phase advance. The detuning of a single cell due to physical damage is a change in the geometry of the cell. If the phase shift is too large, the acceleration is not only less efficient but the emittance (size of the particle beam) can also be affected. However, physical damages in the structure are irrelevant as long as the overall structure accelerates properly. In order to avoid damages, and detuning, it is vital to understand the breakdown mechanism.

DC breakdown mechanism studies [11] have started approximatively 50 years, long before RF study, and so far no strong correlation have been found between the breakdown mechanism in RF and DC [9]. Hence, we need to add new techniques to old ones to enhance our understanding of RF breakdown.

The general hypothesis used to explain breakdown, RF or DC, is based on field emission. The intense electric field present at the surface of the irises of the cells draws an electron current. This current will locally ionize residual gas as well as heat the surface, which release more gas, and producing more ions and electrons. These processes happen at every RF pulse, without causing a systematic arc. The formation mechanism of an arc, due to a build up of electron and ion current, for a single pulse is not yet clear. However, the characteristics of a breakdown are rather well understood [5]. In some cases, such as at the input coupler of some of the NLC structures, the breakdown is not initiated by the electric field but by the induced current along sharp edges due to the high magnetic field [5] [12]. The route toward developing a stable NLC structure pass either by a change of cell material (Mo, W, eventually stainless steel), such as the structure used at CERN

(Conseil Européen pour la Recherche Nucléaire) [13], or/and by a better understanding of breakdown itself [9] [14] [15].

One of the properties of an RF breakdown, as we define it for our application, is characterized by the fact that 80% of the incident power is absorbed by the arc [5]. Simulations, based on plasma spot model, performed to better understand the mechanism of breakdown, do not account for all the loss of energy. A part of this energy is converted into an ion current. Light from excited neutral copper (Cu I) has been observed with a spectrum analyzer at SLAC but also at CERN on similar experiments [13]. The reflected RF also accelerates some electrons toward the upstream cells, this current is known as the dark current. Finally, a part of the energy is converted to heat inside the structure, inducing stress which produces sound waves. Several experiments have been conducted in the NLCTA to account for the missing energy, during a breakdown, with mixed results. Those experiments included radiation monitoring, dark current and acoustic measurements.

In order to locate breakdowns in superconducting RF accelerating cavities, thermal sensors are used [16]. Heat deposited during arcing is recorded by thermometers. Heat is carried by high frequencies phonons (1 GHz to 1 THz), also called optical phonons. Using the same idea for warm (room temperature) accelerating structure, we detect sound wave or low frequency acoustic phonons (100 KHz up to 20 MHz range).

At room temperature (RT), high frequency phonons have a mean free path smaller than their wavelength. As a result heat is propagated in a diffusive way and is described by the heat diffusion equation (equ.1).

$$\rho C_p \frac{\partial T}{\partial t} = Q + \nabla \cdot (k \nabla T) \quad (1)$$

where ρ is the density, C_p is the heat capacity at constant pressure, $\frac{\partial T}{\partial t}$ is the change in temperature over time, Q is the heat added, k is the thermal conductivity.

However, at low temperature (2K), high frequency phonons can propagate in a ballistic way (straight line). This property might be one of the reasons why thermometry gives not only a precise localization for the RF breakdown, but also can locate the active field emitter on the surface of the RF cavity [16], before breakdown. At room temperature, low frequency acoustic phonons also propagate in a ballistic way. Their propagation follows the wave equation (equ.2).

$$\nabla^2 \psi = \frac{1}{v^2} \frac{\partial^2 \psi}{\partial t^2} \quad (2)$$

where v is the speed of propagation of the wave and t the time.

Very good results are obtained for superconductivity cavities with the thermometry method, therefore it is reasonable to try an equivalent technique. We utilized, for our experiment, the same kind of ultrasonic sensor which is used in non-destructive testing [17] [18].

In some cases, several breakdowns can occur on a single machine pulse. We name these events double breakdown, and so on. Such events are difficult to locate with conventional RF techniques, using directional couplers. We will show that the use of an array of acoustic sensors provides an easy way to account for a more accurate number of breakdown as well

as their localization. On the end, this is also a means toward understanding the underlying causes of these arcs.

3 Copper and Acoustic physic

The propagation of a sound wave is described by the wave equation (equ.2 §2). The phonons travel at the speed of sound in the medium and, if the medium is isotropic, the wave can be easily constructed using the classical *Huyghens principle*: "Every point on a propagating wavefront serves as the source of spherical secondary wavelets, such that the wavefront at some later time is the envelope of these wavelets. For a propagating wave of a frequency, f , transmitted through a medium at a speed, v , the secondary wavelets will have the same frequency and speed". Following this principle, the wave takes a spherical shape. If a few sensors are placed on the same plane, the sensors will respond one after the other and a plot of the response versus time of the sensors will show a bow wave.

An example of such a response from sensors after a single RF breakdown in a travelling wave structure of 105 cm long, 5% group velocity (VG), is displayed in Fig.2. The abscissa is equivalent to time in arbitrary units. The time difference between 2 points is of $0.1 \mu s$. The left ordinate is a level of the amplitude also in arbitrary units. The right ordinate is the sensor number. The plot is separated in 3 regions representing 2 consecutive RF pulses and 1 after pulse. The RF breakdown happens in the second pulse and, as a result, the RF power is shut off and no energy is present on the third pulse.

Figure 2: Acoustic bow wave in the T105VG5 accelerating structure following an RF breakdown. Sensors are located 6 cells ($\sim 5\text{cm}$) apart on the spine of the structure, cf Fig.1

However, if the medium is anisotropic, the wave vector and the group velocity vector are no more collinear. The construction of the envelope of the wave becomes more complicated. The anisotropic propagation of elastic energy in a material having different crystal orientation is known as phonon focusing [19] [20].

The primary idea behind phonon focusing is that phonons are wavepackets that travel at the group velocity. In any anisotropic media, an isotropic (in k-space) phonon distribution will result in an anisotropic distribution of phonon flux because of anisotropies in the group velocity. This is seen as a concentration of thermal energy along particular crystal directions. This concentration is easiest to observe in pure, single crystals because inelastic scattering events can randomize the direction of travel of a wavepacket, making the propagation appear isotropic. However, since the phonon scattering decreases with decreasing frequency, it is possible to observe focusing of low frequency phonons, even in imperfect crystals [21]. As a result two sensors located near each other might not receive the same amounts of energy [19]. An example of the existence of the phonon focusing effect in single copper crystal with a 15MHz transducer is shown in [19].

Acoustic phonons are, in the first approximation, propagating ballistically, compared to optical phonon which propagate diffusively. The speed of sound in copper, associated to the propagation of the longitudinal wave also called compression wave or pressure wave (P-wave), is given by :

$$v = \sqrt{\frac{E}{\rho}} = 3560 \text{ m/s} \quad \left\{ \begin{array}{l} E : \text{Young modulus (Pa)} \\ \rho = 8930 \text{ kg/m}^3 \end{array} \right. \quad (3)$$

Inside or at the surface of the copper structure, other sound waves might also propagate. These other waves are shear waves or transverse waves (S-wave or T-wave), and surface waves (Rayleigh-Lamb Wave). In a longitudinal wave, the displacement of the medium (or atoms) is parallel to the propagation of the waves. For shear wave the displacement of the medium is perpendicular to the propagation of the wave. Surface waves propagate at the interface between two media as opposed to through a medium. Many types of surface waves can exist and for our purpose we will consider only the Rayleigh-Lamb waves (R-waves). Rayleigh waves have longitudinal and shear displacement coupled together which travel at the same velocity. The medium oscillates in an elliptical path within the vertical plane containing the direction of the wave propagation [22] [23] [24] [25].

The copper used for building our RF structures is annealed. From the data of the speed of sound in annealed copper [26], we can determine the Young modulus, the poisson ratio (usually $\nu \sim 0.3$ for copper). Plugging those values in the following equations, we can calculate the Transverse v_s and the Rayleigh wave v_R velocities. Equation (6), from Bergmann, gives an approximate value for the Rayleigh wave velocity [17] [18] [27]

$$v_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (4)$$

$$v_s = \sqrt{\frac{E}{2\rho(1+\nu)}} \quad (5)$$

$$v_R \simeq \frac{v_s(0.86 + 1.14\nu)}{1 + \nu} \quad (6)$$

The speed of the longitudinal wave v_p and the shear wave v_s are respectively 4760 m/s and 2325 m/s [26]. The determination from equations (4) and (5) gives a Rayleigh wave speed of ~ 2160 m/s. The equations written above can also be expressed as a function of

the Lamé coefficients λ and μ

$$\lambda = \sqrt{\frac{\nu E}{(1 + \nu)(1 - 2\nu)}} \quad (7)$$

$$\mu = \sqrt{\frac{E}{2(1 + \nu)}} \quad (8)$$

The difference in speed of these waves might in principle be used to determine the location of a breakdown. In the same way seismologists localize earthquakes. The distances between the breakdown and the sensors is of the order of a few cm. The time between the front edge of the pressure wave and a shear wave is in the order of a few microseconds. Electronics are fast enough to separate the edges in time. The problem lies in the energy carried by the waves and the ability to separate the arrival of a successive wave from the tail of the preceding wave. Fast arrival of successive waves might mimic a single wave with long ringing, as in Fig.2.

Depending on the spatial resolution and the precision needed to localize the source of an RF breakdown, going to higher frequencies might be necessary. As the frequency goes up, ~ 10 -20 MHz, the wavelength of the acoustic wave might reduce to the size of a grain (0.5 mm to 0.3 mm for the pressure waves). Grain size in our RF structures (annealed copper) can be up to a millimeter.

Thermal processing (cf §2) and exposure to high pressure of hydrogen changes the way the grains grow and further, the intake of hydrogen might create voids, by reaction with oxide inclusions, at the grain boundaries and dislocations [28] [29] [30]. This intake of hydrogen inside the bulk of the material might ultimately affect the propagation of ultrasonic waves [31], if not properly degassed. However, even if the copper is well degassed, the temperature of the vacuum firing might not be high enough to remove the dislocation or voids created by the intake of hydrogen. Meeting with experts did not rule out this hypothesis [32]. An understanding of the effect of dislocations and grain boundaries on the propagation of ultrasound waves is necessary, as is the attenuation of those waves inside a medium.

Geometric attenuation or attenuation due to the spread of the wave is different for a bulk wave or a surface wave. The bulk waves attenuate following a $1/r$ law where surface wave attenuates as $1/\sqrt{r}$, for a detector located far from the source [17]. In addition to the geometric attenuation, the wave can scatter and diffract [17] [18]. Scattering of the sound wave will occur for inhomogeneous material. Grain boundaries and defects like inclusions and voids are interfaces where an abrupt change of impedance for acoustic waves occurs. This abrupt change create a reflected and a transmitted wave from the initial incoming wave. As a rule of thumb, scattering of sound waves having a wavelength a hundred to a thousand times larger than the grain size is negligible. The scattering is important for waves having a wavelength of the dimension to 10 times the dimension of the grain [18]. Finally, energy attenuation can be due to natural absorption by the medium of the acoustic energy. It can happen by conversion of kinetic energy into heat, by loss of energy through plastic deformation, interactions with dislocation motion. Losses can also occurs by friction between surfaces that slip [17]. We have observed during autopsy of some RF structures, cf. [1] and [33], slip bands. This matter was investigated separately. Also in order to be complete, electron, ion, or phonon - phonon interaction can be sources of loss of energy. These sources of losses tend to be important for phonons of much higher frequencies than the ones with which we are working.

In order to understand how different acoustic waves propagate in annealed copper, a collaboration with the University of Illinois [34] on an experimental and modelling

program have been started. This collaboration will answer questions started by few experiments done at SLAC [35]. In these experiments, using an un-annealed copper block of approximately 10 cm x 10 cm x 5 cm, we found out that high frequencies (above 1-2 MHz) did not propagate well through the block. In the setup, a spark or a laser was shot in one of the side of the block and the sound signal was recorded on the opposite side by an acoustic sensor. Fig.3 shows the response of an acoustic sensor receiving an ultrasonic signal peaked at 20MHz travelling through a copper plates of different thicknesses.

Figure 3: Attenuation of the acoustic response in a Copper block of 0-5 cm thickness with a 20MHz sensor driving & 15MHz sensor receiving

So far, despite all the unknowns, coarse localization of breakdowns in structures have been successful. Acoustic data obtained with the array of sensors placed onto the structure, like in Fig.1, are in very good agreement, Fig.4, with the data obtained by RF analysis, Fig.5. Coarse localization, by quadrant probing, of breakdown initiator inside a cell was also successful. A much finer localization of a breakdown, or a precursor, will require to have an answer on the propagation (attenuation and scattering) of phonons in annealed copper.

4 Conclusion

Localizing damage, by the mean of ultrasonic waves, is commonly used in aircraft and building industry. Applying generally this technique to localize RF breakdowns in accelerators is rather new, and the NLCTA team has been able to successfully demonstrate its effectiveness. A more complete demonstration of this contention will appear in another paper.

The next step in understanding breakdown by the use of acoustic sensor is to have a good knowledge of the propagation of acoustic waves in annealed copper. This under-

Figure 4: Number of single breakdown vs location of the 53 cm long RA (left) and F (right) travelling wave structure; for RF pulses of 170ns 240 ns and 400ns length

Figure 5: Localization of RF breakdown by the use of RF analysis. 120 Hours of operation, at 60 Hz repetition rate, 400 ns Pulse Width. Electric Field: 73 MV/m [36]

standing will help on accurate localization, as is possible in superconductivity cavities [16]. Being able to do so opens the door to knowledge about particules contamination and the importance of surface finish in triggering breakdowns.

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