Spectrometers for RF breakdown studies for CLIC

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Abstract

A $e^+e^-$ collider of several TeV energy will be needed for the precision studies of any new physics discovered at the LHC collider at CERN. One promising candidate is CLIC, a linear collider which is based on a two-beam acceleration scheme that efficiently solves the problem of power distribution to the acceleration structures. The phenomenon that currently prevents achieving high accelerating gradients in high energy accelerators such as the CLIC is the electrical breakdown at very high electrical field. The ongoing experimental work within the CLIC collaboration is trying to benchmark the theoretical models focusing on the physics of vacuum breakdown which is responsible for the discharges. In order to validate the feasibility of accelerating structures and observe the characteristics of the vacuum discharges and their eroding effects on the structure two dedicated spectrometers are now commissioned at the high-power test-stands at CERN.

First, the so called Flashbox has opened up a possibility for non-invasive studies of the emitted breakdown currents during two-beam acceleration experiments. It gives an unique possibility to measure the energy of electrons and ions in combination with the arrival time spectra and to put that in context with accelerated beam, which is not possible at any of the other existing test-stands. The second instrument, a spectrometer for detection of the dark and breakdown currents, is operated at one of the 12 GHz stand-alone test-stands at CERN. Built for high repetition rate operation it can measure the spatial and energy distributions of the electrons emitted from the acceleration structure during a single RF pulse. Two new analysis tools: discharge impedance tracking and tomographic image reconstruction, applied to the data from the spectrometer make possible for the first time to obtain the location of the breakdown inside the structure both in the transversal and longitudinal direction thus giving a more complete picture of the vacuum breakdown phenomenon.

Keywords:
CLIC, X-Band, Accelerating structures, RF breakdowns

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1. Introduction

Following the discovery of the Higgs particle at the LHC [1][2] and in anticipation for further revelations hiding in the data of the LHC Run2 [3] there is a demand for precise measurements at a lepton collider operating at TeV energy range. These high precision studies are necessary to reveal the exact nature of the new very heavy particles.

One of the leading candidates is the Compact Linear Collider (CLIC). CLIC is an international collaboration based at CERN dedicated to developing the technology for an $e^+e^-$ linear collider for the range of energies from 250 GeV to 3 TeV. It is based on high-gradient, 100 MV/m, normal conducting accelerating structures, low emittance beams and a two-beam power generation scheme [4]. The CLIC idea is to generate high power radio frequency waves (RF) by decelerating a high intensity low energy beam. This power is then transferred to and used to accelerate a low intensity beam to extremely high energies. The CLIC two-beam acceleration scheme achieves a more efficient power distribution to the accelerating structures along the whole collider as compared to traditional klystron power sources.

Compared to an accelerator using superconducting technology, CLIC has very low power consumption in between the pulses (very low duty factor of 0.00078% assuming 156 ns RF pulse flat-top and 50 Hz repetition rate) and with its high accelerating gradient will be able to keep the length, and thus cost, of the collider within reasonable limits [5]. Key performance limitation is the achievable field gradient which is suppressed by the breakdown level of the electro-magnetic field in the vacuum of the accelerating structure, the so-called RF breakdown. In order to achieve high luminosity the RF breakdown rate is required to be at the level of $10^{-7}$ breakdowns per RF pulse per meter, which corresponds to about 1% of luminosity loss.

Breakdown physics. The RF breakdown phenomena is a highly complex process and a detailed understanding of all the physics involved is not yet available. Many models were put forward during the years and they generally divide the process into several steps [6][7][8].

- Most models assume that the field emissions are an important part of the initiation process. During normal operation when RF field is inside the structure the electrons are liberated from the surface’s micro-protrusions which become field emitters. This phenomenon is well understood and it follows the so called Fowler-Nordheim law [9]. These field-emitted electrons are influenced by the electro-magnetic wave inside the cavity, accelerated and ejected from the cavity. These electron currents measured during normal operation are referred to as dark current. What exactly triggers a vacuum breakdown is not known but it is believed that the first step is a mechanical erosion of the surface at the emitter point which produces neutral fragments [7].
• These fragments are then ionized by the field emission currents, forming a plasma. Secondary electron emission occurs and more neutral fragments are liberated and later ionized due to surface bombardment leading to rapid increase of the plasma density [10].

• This avalanche process of rising density results in a sheath potential forming above the emitter and the formation of an arc. The local field increases and the field emission, which depends exponentially on the field value, is reaching current densities of the order of A/µm and forming a full arc. Electrons in the plasma can be captured by the RF field still present in the structure, accelerated and ejected out. These electron currents are more than one order of magnitude larger than the dark current and are referred to as the breakdown current. After the plasma is stripped of electrons the remaining ions can explode under the influence of their mutual Coulomb repulsion [11].

• This is where the cavity surface is suffering damage. The field emitter melts and further bombardment by electrons and ions creates new emitters which in turn quickly explode and evaporate. The process continues as long as RF power is supplied to the structure [12].

Even with this understanding there are still many unanswered questions. For example we still do not know what triggers a breakdown. One theory suggests that the field emission currents cause pulsed local heating of micro-protrusion which acts as a breakdown trigger [13]. Based on this theory a power flow model introducing new field quantity, the modified Poynting vector, taking into account active and reactive power flow on the surface of the structure explains the experimental data related to the high-gradient limit of the RF breakdowns [14]. Yet, this model does not give an answer to the question as to why there is breakdown in a particular pulse after millions of non-breakdown pulses when field emitters are constantly heated? The so called stress model, looks instead into tensile stresses that the high electrostatic field puts on the surface which can cause cracks or dislocation on the surface. The formation of the fractures can be an onset of a breakdown and with pulsed heating present – a main trigger for a breakdown. The model assumes that the breakdown rate is proportional to the number of defects in the crystalline structure of material [15][16]. There are other open questions concerning physics of RF breakdowns and the search for understanding of this phenomenon requires experimental data.

Diagnostics. Studies of RF breakdown have mostly focused on statistical analysis of the rate at which the breakdown of the RF fields in the accelerating structures occurs as a function of the microwave pulse length and power while slightly modifying the shape of the accelerating structure with each iteration. This is routinely done during RF processing (also called conditioning) of the structure [17]. The monitored signals are the amplitudes and phases of the arriving, transmitted and reflected RF pulses from the cavity as well as the ejected electron currents [18][19]. In some cases the structure is later cut-open and the
surface is analyzed with microscopic methods. The dark current which absorbs part of the RF energy and causes radiation is a precursor of plasma formation and because of that is also seen as a precursor of breakdown. Studies of dark and breakdown currents can tell us about the position and intensity of the arc as well as of plasma’s size and density. Furthermore acoustic vibrations, X-ray and visible light emissions can be observed during RF breakdown [20].

All these parameters are necessary in testing the theoretical models and improving them. However, a breakdown is most likely not due to a single process, but a complicated and complex phenomena. Because of this the results from the statistical studies are sometimes contradicting and difficult to apply directly to theory [21]. These standard measurements do not give full insight into the onset of breakdowns and what is going on inside the structure. A possibility to analyze each breakdown event separately and sort them out depending on the characteristics helps to give a clearer picture.

2. CLIC test facilities

In recent years interest in RF breakdowns has increased in the framework of the collaboration around the CLIC Test Facility (CTF3) that aims to develop the technology required for CLIC and other applications such as free electron lasers (FEL). One of the first objectives of the CTF3 collaboration was to build a test-stand where CLIC cavities could be tested with full power generated in special power generating structure.

30 GHz test-stand. To this end a dedicated beam line, 30 GHz power generating structure and power transfer line have been installed at CERN. This test-stand was in operation for several years from 2005 running up to the nominal CLIC accelerating gradient of 150 MV/m at 30 GHz and beyond the nominal pulse length [22]. With this test-stand the CTF3 collaboration was investigating a number of different materials and performing breakdown studies in an effort to find ways to increase achievable accelerating gradient [20] [23]. The test-stand included standard breakdown diagnostics i.e. signals of incident, reflected and transmitted power and a signal from a Faraday cup installed outside the structure. In addition to a negative signal from fast ejected electrons (measured on a nano-second time scale) occasionally positive signal from ion current (measured on a µs time scale) was recorded[24]. The presence of escaping ions could be explained by Coulomb explosion occurring at the surface during surface micro-fracture producing fragments in the presence of the electron currents [15] or later when part of the electrons in the plasma formed above the breakdown site are accelerated in the RF field, but the remaining lumped ions explode under the influence of their mutual Coulomb repulsion [11]. Since the ion current signal might be used to estimate the erosion rate of material from the accelerating structures due to RF breakdown it was further studied at the next test facility operated by CTF3 collaboration the so called Two-beam Test-Stand (TBTS).
The Two-beam Test-Stand. The main objective for the TBTS is to demonstrate feasibility of the CLIC two-beam acceleration scheme [25]. So called drive and probe beams are available for test and verification of high gradient acceleration as well as for the RF breakdown studies. The TBTS is build with extensive beam diagnostics and it is therefore particularly well suited to investigate the effects on the beam of RF breakdown in the high gradient accelerating structures.

As mentioned before, a RF breakdown besides disrupting the flow of energy inside the structure creates an arc with electron and ion currents. The electromagnetic interactions between the beam bunches and these currents might significantly affect the beam [26]. The impact that RF breakdowns have on the beam in term of transverse momentum kick as well as on beam energy due to loss of the acceleration in a cavity undergoing an RF breakdown was measured at the TBTS [27]. The results showed that the kick can cause up to 90% of geometric luminosity loss if would occur at the early stages of the main CLIC linac, which once again stressed the need for better understanding the underlying physics of breakdowns.

Flashbox. One of the instruments aimed for the non-invasive measurements during the TBTS operations is the so called Flashbox [28]. It is using beam-line corrector magnet for measuring the energy and charge or the mass-to-charge ratio of the electrons and ions from a breakdown event. The accelerator beam can pass the detector and the corrector magnet undisturbed while charged particle emitted after the breakdown can be directed to and pick up by the detector. Positive and negative particles are measured on different detectors on opposite sides of the beam axis facing each other. Each single plate forms a capacitor, which is charged by impacting particles and later read out via a 50 Ω resistor. The detectors are placed longitudinal along the beam line and the position of the signal is used to measure the energy of the particles, see fig. 1.

![Figure 1: Interior of the Flashbox showing eight copper plates mounted along the beam direction and the current transformer at the front.](image-url)

The Flashbox is installed 1.7 m downstream of the accelerating structure.
(ACS). A steering dipole magnet between the structure and the Flashbox, allows to control the spectrum range of emitted charged particles measured by the detector. The Beam Position Monitors (BPM) in the line provide mean position and intensity information of the passing particles, fig. 2.
RF power signals measured at the accelerating structure are used for detecting a breakdown. The indication is a sudden drop in the RF transmission followed by the increase in the RF reflected signal. This is typically accompanied by electron emission measured by upstream and downstream BPMs. For a 400 ns RF pulses with 90 MW peak power, electron pulses with duration up to 250 ns were measured at the Flashbox, see fig. 3.

Based on the applied magnetic field the energy of the majority of the electrons have been found in the range between 1 keV and 4 MeV during breakdowns at accelerating gradients of about 140 MV/m. Positive signals were as well measured during the experiment, but, as expected, at much later arriving time, typically between 1 to 1.5 \( \mu \)s. From this information the velocity of the ions was estimated between 0.4 % and 0.6 % of the speed of light while the mass-to-charge ratio was estimated between 1.2 u/e and 2.5 u/e when taking into account the applied magnetic field, see fig. 4.

While it is not possible to uniquely assign this result to one ion type we believe it to be \( \text{H}_2^+ \) (14-30 keV). We attribute its presence to a missing baking step after hydrogen treatment during the fabrication process, which left hydrogen trapped in the walls of the cavity. The hydrogen could later be release during the breakdown. Further experiments are planned to search for other species of ions ejected from the cavity during breakdown.
3. X-band stand alone test-stands

RF conditioning of an accelerating structure entails processing with large number of RF pulses during a long period of time. In view of the large number of accelerating structures to be tested, it is not feasible to operate the entire CTF3 complex for this purpose. For this reason the CTF3 collaboration has in addition built up two high gradient test-stands for RF accelerating structures at CERN, so called "XBox" stations [29].

The XBox1 has been in operation for two years while the XBox2, which is an improved version of the XBox1, has been commissioned just recently. Both test-stands consist of a solid-state high-voltage modulator, a 12 GHz klystron, vacuum tube amplifier, a pulse compressor and a waveguide distribution system that can be run with a much higher repetition rate than the TBTS. The device under test is monitored and interlocked for breakdown events with incident, transmitted and reflected RF signals as well as Faraday cups and vacuum signals. The high rate operation of these test-stand gives possibilities for extensive statistical studies of the RF breakdown phenomena [19].

*Uppsala/CLIC X-Band Spectrometer (UCXS).* The main drawback of the breakdown studies at the TBTS is the low drive beam repetition rate of 0.8 Hz. Since the breakdown rate varies from $10^{-6}$ to $10^{-3}$ breakdowns per RF pulse per meter the required time for statistically significant experiment is rather long and the working conditions of the accelerator can change substantially during the run. That is why the second instrument, called Uppsala/CLIC X-Band Spectrometer (UCXS), was installed at the XBox2 test station capable of running at full power at 50 Hz.

The UCXS is a general-purpose system for detection and measurements of the dark and breakdown currents during conditioning of new accelerating structures for CLIC. The aim is to measure the spatial and the energy distribution of the electrons and ions ejected from the accelerating structure in different operating conditions within a single RF pulse. These measurements can be correlated with the location of the breakdown inside the structure using information from the incident, reflected and transmitted RF power, giving in that way a complete...
picture of the vacuum breakdown phenomenon. The UCXS consists of a dipole magnet, a collimator, a fluorescent screen and a fast CCD camera, see fig. 5.

Figure 5: The spectrometer setup. From the left is shown the cavity followed by the first vacuum chamber housing the collimator, then dipole magnet and chamber with the fluorescent screen with the view-port for the camera (the camera with the optical line is not in the picture). A Faraday cup closes the setup on the right.

The charged particles ejected from the accelerating structure during breakdown are first collimated and then enter the magnetic field of a dipole magnet. After the magnet we can observe an energy-dependent pattern formed by the particles impinging on a fluorescent screen. The holder holds two collimator patterns (a single 10×0.5 mm slit and a 0.5 mm diameter pin-hole) and is mounted on a linear actuator allowing to place the desired pattern in front of the beam or to fully extract the collimator. The collimator is made of 5 mm tungsten plate and is electrically insulated from the actuator and can be used to measure the charge collected on the plate.

The electrons are registered on a 100×50×0.5 mm YAG:Ce fluorescent screen. The screen plane forms 30° angle with the beam axis in order to allow for an optical line to the camera at 90° angle. We use a mirror to reflect the image onto the 2M pixels CCD camera capable of acquiring 50 frames per second. The camera is equipped with a lens and a stepper-motor-driven focuser. The frame of the screen is mounted on the linear actuator with a stepper motor which allows us to place the screen at different distances from the beam axis as well as to fully retract it out of the beam.

The setup is designed to operate with an integrated magnetic field strength between 0.2-10 mTm that allows to resolve almost the entire expected energy range from 0.5 to 20 MeV. The energy resolution of the UCXS was estimated using GEANT4 [30] simulation and found to be between 10-20 % for kinetic energies below 6 MeV, 20-35 % below 12 MeV and reaching more than 40 % for energies above 15 MeV.
First results from the UCXS. The UCXS was commissioned during conditioning of a special deflecting cavity (crab cavity) developed for the final beam delivery at the CLIC interaction point [31]. That cavity was replaced in the Fall 2015 by the CLIC acceleration structure CLIC-T24-OPEN manufactured by milling structure out of two halves instead of machining and then brazing single cells [32]. The conditioning process of this cavity is still ongoing. Fig. 6 presents schematics of the setup and the acquired signals.

![Schematic view of the XBox2 setup during commissioning with cavity diagnostics.](image)

Both amplitude and phase of the incident, transmitted and reflected power signals are measured with directional couplers. Emitted charges are recorded with two Faraday cups and collimator plate. Vacuum levels are monitored at strategic points in the setup but are not indicated in the schematics.

With the electrons collimated by a single slit one would naively expect also a single slit image on the screen. However this is seldom the case. We often observed smeared or multiple slits images on the screen instead. See comparison in Fig. 7, left.

![Fig. 7: Left: Two breakdown events recorded on the screen. Although a single slit collimation was used in both cases, the bottom image clearly shows multiple features. Right: Projection of the lower-left image with three visible slits. Distance between peaks is almost the same, approximately 2 mm. Fourth, smaller peak, is visible to the left.](image)

The event in fig. 7, right, shows multiple slit images with a common distance between the observed slits of approximately 2 mm. This would corresponds to the transverse movement at the source, i.e. inside the cavity, of about 1.8 mm.
Richness of features on the spectrometer screen corresponds most of the time with the activity on the RF reflected pulse, both amplitude and phase. Fig. 8 shows an example of an image and the corresponding RF signals. While there is a dominant representation of the slit in the center one can also observe a second parallel slit image translated both horizontally and vertically.

The top-right plot presents the amplitudes of the incoming, transmitted and reflected signal. As mentioned earlier (see section 2), rapid decrease of the transmitted signal accompanied by the rising reflected signal is the clear indication of a RF breakdown.
**Longitudinal dynamics.** A strong reflected signal emanating from the accelerating structure in the backwards direction, indicates a significant impedance mismatch appearing in the structure. Sometimes the reflected signal shows a prominent oscillatory pattern in the amplitude with associated jumps in the relative phase of incident and reflected wave as shown in fig. 8. The pattern of minima and maxima resembles the standing wave ratio resulting from a mismatched load, when the load is moving towards the source.

It is important to note that the standing wave that builds up upstream of the discharge site has a higher field amplitude at repetitive locations, where it may trigger a next discharge, which moves the short upstream to the new discharge site. We are therefore interpreting each of the peaks in the reflected signal as a start of a new discharge build-up. The incoming power is lost on "feeding" the breakdown. We propose a model to, in a quantitative way, determine where inside the structure and what the impedance of the short is. In the following discussion we use the concepts and notation from the book by Ulaby and Ravaioli [33].

We model the RF structure as a matched, lossless transmission line with impedance $Z_0$ and a wave with frequency $f = \omega/2\pi$ and propagation constant $\beta = 2\pi/\lambda$, where $\lambda$ is the wavelength. The phase velocity of the propagating wave has to match the speed of the electrons and is equal to the speed of light. We denote the right moving incoming voltage pulse by phasor $\tilde{V}^+(z)$ and the reflected pulse by phasor $\tilde{V}^-(z)$. The discharge in the model spontaneously appears as a impedance $Z_s$ parallel to the matched load $Z_0$. We define also a spatial dimension describing distance from the load, $d$, that starts at the load with direction opposite of $z$. The geometry is shown in fig. 9.

![Figure 9: Model of the transmission line with characteristic impedance $Z_0$ and phase propagation constant $\beta$ terminated by a combined impedance $Z_L$ formed by matched impedance $Z_0$ and impedance $Z_s$ emerging during breakdown. The load is located at $d = 0$ and the directional coupler is at position $d$.](image)

As soon as the discharge forms the load impedance becomes $\frac{1}{Z_L} = \frac{1}{Z_0} + \frac{1}{Z_s}$.

The ratio of incoming and reflected voltage at the load defines the reflection
The reflection coefficient \( \Gamma \) can be expressed as:

\[
\Gamma = \frac{\tilde{V}^-(d=0)}{\tilde{V}^+(d=0)} = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{-1}{1 + \frac{2Z_s}{Z_0}} = -\frac{1}{1 + 2z_s} \tag{1}
\]

where we express the reflection coefficient in terms of \( Z_s \) and introduce normalized impedance \( z_s = \frac{Z_s}{Z_0} \). The parameter \( \Gamma \) is in general a complex quantity, \( \Gamma = |\Gamma|e^{j\theta} \).

To compare the incoming and reflected signals recorded by the directional coupler, we have to take into account that the incoming wave has to propagate to the discharge site and collect a phase advance \( e^{j\beta d} \). The reflected signal accumulates the same phase advance when traveling back to the coupler. We find that:

\[
\frac{\tilde{V}^-(d)}{\tilde{V}^+(d)} = |\Gamma|e^{j\theta_T}e^{-2j\beta d} = \frac{-e^{j(\theta_T-2\beta d)}}{1 + 2z_s} = e^{j(\pi + \theta_T - 2\beta d)} \tag{2}
\]

In a discharge, the impedance is dominantly resistive, \( \theta_T \approx 0 \), most of the energy is dissipated in igniting and then sustaining the plasma. Therefore, we can treat \( \Gamma \) as a real quantity determining only the amplitude of the reflected signal. We assume that the distance \( d \) is not too large that we can avoid to take the delay between the arrival time of incoming wave and the reflected wave into account. We therefore confine ourselves to slowly varying processes, which are slower than the round-trip time between detector and discharge site \( \tau = \frac{2d}{c} \) which is normally a few ns. In the experimental setup at the XBox2, we measure the amplitudes and the phase of incoming and reflected signals and can express the ratio of the signals as \( \tilde{A} \).

\[
\tilde{A} = \left| \frac{V_{ref}(t)}{V_{inc}(t)} \right| e^{j(\phi_{ref}(t) - \phi_{inc}(t))} = |A(t)|e^{j\Delta \phi(t)} = \frac{e^{j(\pi - 2\beta d(t))}}{1 + 2z_s(t)} \tag{3}
\]

To stress that the measured quantities are time-dependent, we introduced time-dependence explicitly. We can now compare real and imaginary parts and find the relations for the distance between discharge location and the coupler and the normalized impedance of the discharge.

\[
z_s(t) = 1 - \frac{|A(t)|}{2|A(t)|} \tag{4}
\]

\[
d(t) = \frac{\pi - \Delta \phi}{2\beta} \tag{5}
\]

Fig. 10 shows the results from the model applied to crab cavity data. We observe one or several peaks in the impedance spectrum as a function of distance. The separations between peaks correspond well to the cell length of the cavity, 8.3 mm. The intensity in the image is correlated with the measured impedance while the events with images with multiple features have also higher number of impedance peaks. This strengthens our hypothesis that new breakdowns can
establish themselves during the same RF pulse. Formation of the plasma is a relatively fast process, on a timescales on the order of 10-50 ns. With cavity operated at a pulse length of 200 ns there is time for more arcs to form.

Transverse breakdown location with image deconvolution. The information about transverse location of the breakdown is preserved in the image on the screen. We can treat our setup as a linear system with source (electron emission sites), object (collimator) and image plane (screen) and look for analytical solution.

An image can be represented as a convolution of a space-invariant point-spread function (e.g. slit or pinhole) with the source distribution. In our case source distribution corresponds to the distribution of the electron emitters inside the cavity in the transversal plane. Different direct (e.g. Fourier or Wiener) and indirect (e.g. Lucy-Richardson) methods of two-dimensional image deconvolution were tried [34]. All these methods suffer from high sensitivity to noise and the implementation of the point-spread function and resulted in artifacts and spurious features produced at the source.

Instead we developed a procedure based on tomographic methods. In this approach the source distribution is obtained by calculating a series of one-dimensional deconvolutions. First the image is divided into columns with the width corresponding to the width of the slit. Then each projection from the column is taken to directly solve the inverse problem, i.e. deconvolution with now one-dimensional slit function, see fig. 11. Prior to the procedure the image is processed with Wiener adaptive noise-removal filter.

Using our method we avoid the influence of the width of the slit on the constructed image. This method proved more robust in the presence of noise yielding better results than any 2D convolution methods. The disadvantage of the method is the reduced resolution.

In fig. 12 we present results of the reconstruction of the breakdown events.
Figure 11: Illustration of the tomographic deconvolution method. The image on the right is divided into columns with the width related to the width of the slit. Each projection is used in one-dimensional deconvolution with a slit function to create a full representation of the source distribution.

The three figures on the left show the distribution of the source of the electrons inside the cavity while the small insert in each figure unveils the original image on the screen. Single, double and triple slit image was chosen for the illustrative purpose. The image in fig. 13 shows a superposition of 279 events, collected during one week of operations, giving a cumulative representation of electron source distribution inside the cavity during breakdowns. The circle of 10 mm diameter is placed at the center of mass of the image (average coordinates, weighted with the intensity) to be compared with the maximum iris size of the T24-OPEN cavity of 6.3 mm with included one standard deviation. The same circle is also shown in the images from single events. Pixel size corresponds to 1.25 mm.

Figure 12: Three examples of reconstructed breakdown events: the distribution of the source of the electrons inside the cavity with small inserts showing the original image. The circle of 10 mm diameter is placed at the center of mass of the image to be compared with the maximum iris size of 6.3 mm. Pixel size corresponds to 1.25 mm.

In the cumulative distribution we observe an excess of events corresponding to vertical direction. This coincides with the joint between the two halves of the T24-OPEN cavity and could indicated higher probability of the breakdown along that juncture. It should be noted that the longitudinal position inside the structure was not taken into account, however it only influences the transverse position radially and adds uncertainty of approximately one pixel.
The two investigations are complementary, the transverse effects can be analyzed with the spectrometer and longitudinal dynamics derived from analysis of RF signals. This gives a unique possibility for a very complete insight into behavior of the RF breakdowns.

4. Conclusions and outlook

Vacuum discharges have been studied for over a century, yet still there is disagreement about the nature of the mechanisms that cause them. Most of the studies in the field until now focused on statistical investigations relating RF pulse parameters with breakdown rate in order to optimize the performance of the RF structures. Yet the consensus among the theory groups is that there is not a single process leading to breakdown but rather a combination of many.

In order to extend our understanding of RF breakdowns we want to analyze a breakdown by combining as many information as possible from a single RF pulse. Such a data are necessary to confirm fundamental assumptions in the theoretical models and to guide their further development.

To this end two instruments are now developed. The Flashbox - to study the ion and electron currents emitted during a breakdown with a beam passing through the accelerating structure - gives an unique possibility to put the breakdown currents in context with accelerating gradient and beam kick, which is not possible at any of the other existing test-stands. In the first experiment the ejected electron energies have been found in the range 1 keV to 4 MV at accelerating gradients of about 140 MV/m. We found the evidence of the $H_2^{+1}$ ion emission and the program continues searching for other ions species and reconstructing the time-resolved electron energy spectra.
The UCXS, a general-purpose system for detection and measurements of the dark and breakdown currents during conditioning of new accelerating structures for CLIC, has also been successfully installed and commissioned. The spectrometer allows to for the first time simultaneously measure transverse and longitudinal dynamics of the breakdown within single RF pulse. We proposed a model where the field reflection can be seen as reflection on a mismatched load in the structure. That mismatch in the load can be interpret as plasma growth at the breakdown site. The first results are encouraging, we observe multiple structure in the impedance-distance function which we believe represent a breakdown cell migration. We also add to the analysis “toolbox” a robust procedure for the extraction of the transverse breakdown position providing us with the size and displacement of the discharges during RF pulse.

The data collected during first experiments with the UCXS are being analyzed and further runs are now on the way with a normal CLIC accelerating cavity installed. This will give us the opportunity to fully explore the potential of the spectrometer with the magnet and focus on the energy distribution of the charged particles produced during single RF breakdown.

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