NOVEL DIAGNOSTICS FOR BREAKDOWN STUDIES*

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Abstract

Electrical breakdown limits the achievable gradient in in high energy accelerators such as the CLIC linear collider. Ongoing experimental work is trying to benchmark the theoretical models that focus on the physics of vacuum breakdown which is responsible for the discharges. The CLIC collaboration has commissioned a dedicated 12 GHz test-stand to validate the performance of accelerating structures and observe the characteristics of the RF discharges and their eroding effects on the structure. A versatile system for detection of the dark and breakdown currents and light emission is being developed for the test-stand. We intend to determine the spatial and the energy distribution of the electrons and ions ejected from the accelerating structure in different operating conditions. For this we built a spectrometer consisting of a dipole magnet, a pepper-pot collimator, a fluorescent screen and a fast camera. These measurements can be correlated with e.g. the location of the breakdown inside the structure, using information from the incident, reflected and transmitted RF powers, giving in that way a complete picture of the vacuum breakdown phenomenon.

INTRODUCTION

Linacs with accelerating gradients in the range of 30 to 100 MV/m (with surface electric fields in the range of 100 to 300 MV/m) are now being proposed for a diverse spectrum of applications including linear colliders like CLIC [1], free electron lasers [2], medical accelerators [3] and Compton-scattering light sources [4]. If high enough accelerating gradients can be achieved, the length of the linac can be greatly reduced, which will in turn require considerably smaller space for housing the accelerator complex. A main focus has therefore been to achieve higher accelerating gradients, without compromising the reliability of the accelerator. However, increasing the electric field in the acceleration gaps of a linac increases the probability of electrical breakdowns in the cavity.

The knowledge of the physical processes inside the accelerating structure (ACS) during an RF pulse, and especially during breakdowns, is limited. The proposed theory is that the electric field can be enhanced at some particular position on the surface due to impurities or geometrical features. These positions, called emitters, are the source of primary field-emitted electrons present even under normal operation conditions. These electrons can be accelerated by the RF pulse and leave the structure with a kinetic energy dependent on the accelerating gradient and the length the ACS. The field emission current ejected outside the ACS is usually referred to as the dark current.

High electric field and temperature effects at the emitters lead to the emission of not only electron but also neutral molecules. Negative charges however dominate and process of ionization starts taking place. Due to collisions between electrons and gas molecules as well as the bombardment of the walls, more and more ions are created leading to formation of plasma. When high enough amount of free charges are present a breakdown occurs forming a vacuum arc. The arc becomes self-maintaining with rapidly increasing amount of free charges. Electrons present in the plasma are accelerated in the RF field and removed while the remaining ions cloud can explode under the influence of their mutual Coulomb repulsion. This effect has been reported in [5]. A current detected outside the structure during a breakdown can be an order of magnitude higher than that of the dark current.

Empirically it is known that the breakdown rate can be reduced by conditioning the accelerating structures during long periods of operation at high field but this process is not well understood. In order to significantly reduce the time needed to condition the cavities and, in particular, to open the possibility to go to even higher gradients than 100 MV/m, detailed research on the mechanism and nature of these high voltage discharges is required. Therefore the CLIC collaboration has prepared a dedicated test-stand to condition the accelerating structures for CLIC at CERN [6].

The Uppsala accelerator group joined this effort with intention to add diagnostic capabilities to the CERN test stand. For that purpose we have been developing a system with an external magnetic spectrometer for measurement of the spatial and energy distributions of the electrons emitted from the acceleration structure.

THE PRESENT X-BAND KLYSTRON TEST-STAND

Considering the vital and absolute necessity of a sufficient number of high power tests of structures to validate the feasibility of the CLIC technology, a new klystron-based stand-alone power source operated independently of the main facility at CTF3 has been constructed by the CLIC collaboration at CERN. It consists of a solid-state high voltage modulator (ScandiNova) and a single 12 GHz klystron

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(SLAC XL5 type) feeding the structure under test. In order to arrive at the nominal CLIC pulse length of 270ns, the klystron output pulse is compressed using a pulse compressor with the peak power increased up to a factor of 2.7. The general layout of the 12 GHz test stand is presented in Fig. 1. The main parameters of the klystron are shown in Table 1 and further details can be found in [6].

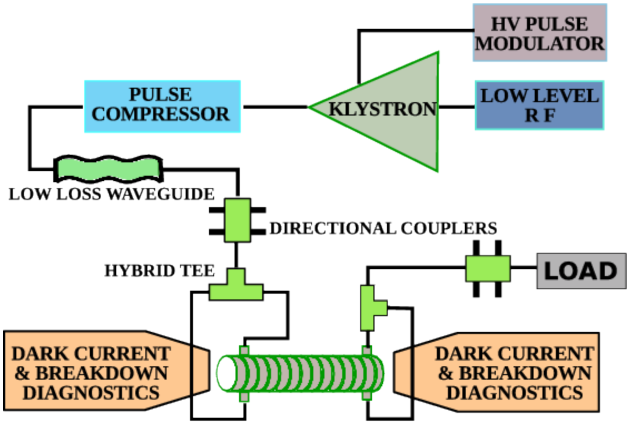

Figure 1: The klystron can deliver a peak RF power of 50 MW at 11.9942 GHz. The RF pulse is modulated by the low level RF system and compressed by a pulse compressor. The RF power is transferred to the accelerating structure test area for conditioning and diagnostics.

Table 1: The Main Parameters of the X-Band Klystron Used for the Test-Stand

KLYSTRON	
Frequency	11.9942 GHz
Peak power	50 MW
Repetition rate	50 Hz
Pulse length	1.5 μs

The ACS receives RF power from the klystron and the incident, reflected and transmitted power is measured at the directional couplers (see Fig. 1) with diode detectors and I-Q detectors for amplitude and phase. Two Faraday cups are installed on the beam axis at each side of the cavity providing information about the number of electron emitted from the ACS during the RF pulse.

NEW DIAGNOSTICS

This set of standard diagnostic devices will be complemented by a novel spectrometer setup in order to measure the electrons and ions that emanate from the structure [5].

The Design of the Spectrometer

The plan is to use different slits and pepper-pot grids in order to obtain the spatial information about the ejected electrons or ions within one RF pulse. The pepper-pot concept is that the electrons hit a plate with a number of small holes arranged in a matrix of lines and columns. The passing particles, defined by this pattern, form beamlets and continue further where they can be observe on e.g. a viewing screen. In our design we put a dipole magnet directly after the pepper-pot grid to get an energy-dependent pattern on the screen behind the magnet. The viewing screen where the light spots are observed, will be read out by a fast camera. The schematic view of the spectrometer and a example simulation of the results is shown on Fig. 2. From each line in the pattern, each corresponding to one of the beamlets, we can extract intensity and energy distribution belonging to this particular angular position. In Fig. 8 we give an estimate of the energy resolution obtained that way.

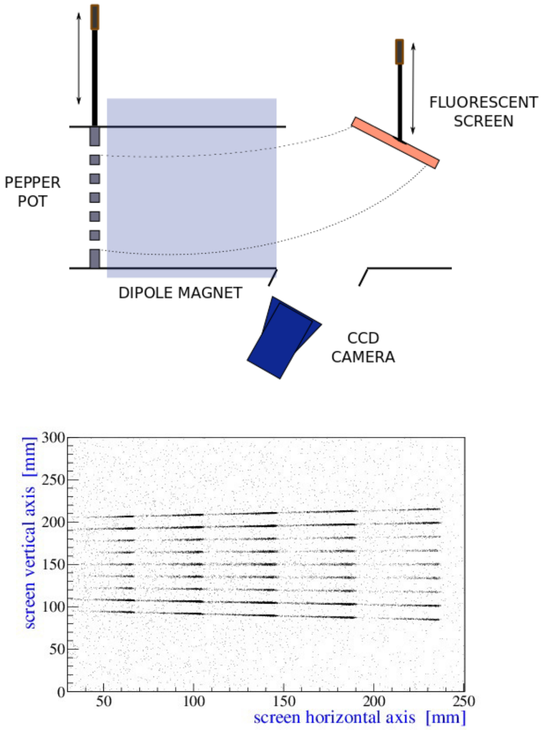

Figure 2: Top: Schematic view of the spectrometer function. Pepper-pot collimator is followed by a bending magnet and a fluorescent screen. Bottom: Simulated result observed on the screen. Each passing beamlet will form an energy dependent pattern on the screen.

It is evident that the design of the hole pattern has to be adapted to the expected width of the energy bands in order to avoid overlap of the beamlets. To allow for maximum flexibility of the system we use a plate holder where two collimator grids can be mounted simultaneously. The holder is fitted on a linear actuator which is operated by a stepper motor with possibility to fully extract the grids from the beam, see Fig. 3. The collimator plates are electrically insulated from the actuator and can be used as a Faraday cup.

The electrons that pass through the plate and continue

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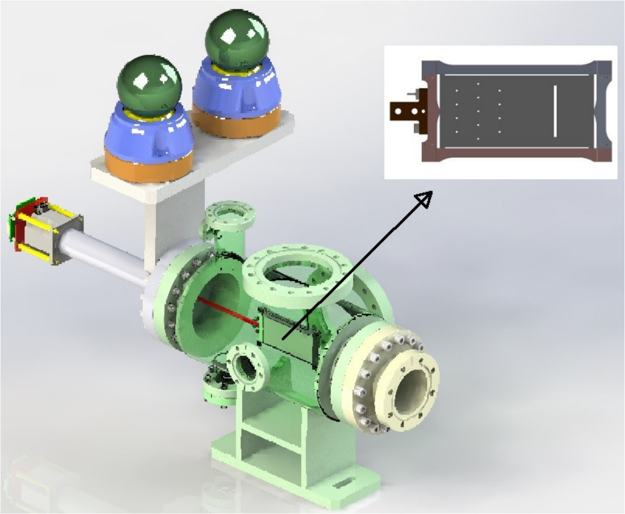

Figure 3: The vacuum chamber with the collimator frame mounted on the linear actuator. The collimators can be fully extracted from the particle pathway. Indicated is the frame of the collimator fitting two separate 50x50mm patterns.

through the magnet are registered on a 100x50x0.5 mm YAG:Ce fluorescent screen [7]. The screen plane forms 30 degrees angle with the beam axis in order to allow for a direct optical line to the camera at 90 degree angle (see Fig. 4). This way we avoid defocussing of the image due to depth-of-field of the camera system. We use an elliptical mirror to reflect the image onto the CMOS sensor of a 2M pixels, 50fps camera which is protected from radiation inside a lead shielding. The camera is equipped with a lens and a stepper-motor driven focuser. The frame of the screen is as well 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.

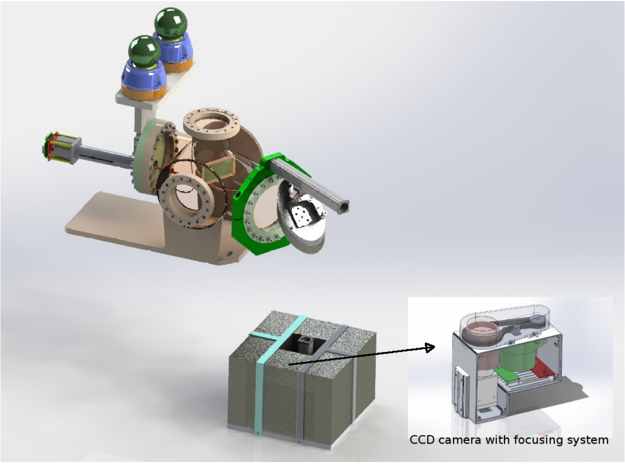

Figure 4: Vacuum chamber with the fluorescent screen. Visible are also elliptical mirror and the lead shielding holding the camera with focusing system.

A Faraday cup is located in the forward direction. It will allow us to measure the electron and ion currents when both the screen and the collimators are removed. Fig. 5 presents the whole setup.

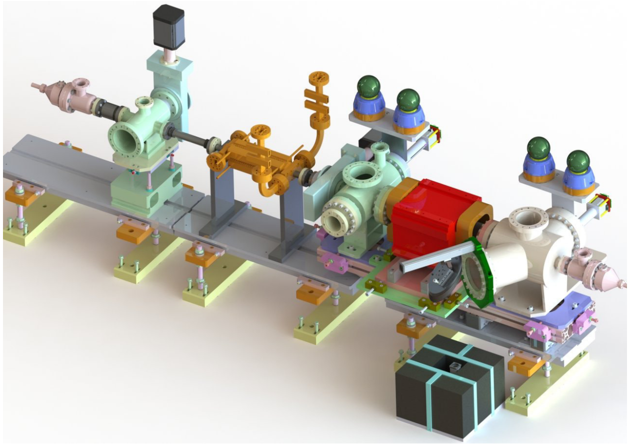

Figure 5: 3D-model of the diagnostic setup. Shown in the middle is the accelerating cavity in yellow. Following to the right is the first vacuum chamber housing the collimator, then dipole magnet in red and chamber with the fluorescent screen with the view-port for the camera. A Faraday cup is located in forward direction.

A typical electron dark current measured on a Faraday cup is of the order of few mA per RF pulse. The breakdown current can be up to two orders of magnitude higher, but is lasting only a few ns. Taking into account the geometry of the spectrometer setup one can expect $\approx 10^9$ electrons passing the 10x0.5mm slit. That is enough for spectroscopic analysis with the magnet.

Simulations

A simplified model of the diagnostic setup was implemented in GEANT4 [8] simulation in order to optimize absorber material and thickness, magnet strength and the geometry of the setup. The model included a slit or a single pepper-pot, magnet and a screen. The secondary interactions and their effect on the background situation during image analysis were taken into account. Fig. 6 presents a plot with particle tracking inside GEANT4 simulation.

We varied several parameters in order to optimize the setup e.g. the size of the slit and holes, the distance to the screen, the length and the strength of the magnetic field, the electron beam divergence. The size of the screen was kept intentionally larger in order to register electrons with full range of energies. In the real setup we will be able to move the screen and in that way scan all the energies. The example of the spectra obtained during simulation of 4×10^6 electrons generated with a flat energy distribution with 5 mm-thick tungsten plate with 1.5 mm slit and 30 cm magnet with strength of 5 mT are shown in Fig. 7.

The simulations resulted in the choice of tungsten as a material for the collimator for which 5 mm thickness is

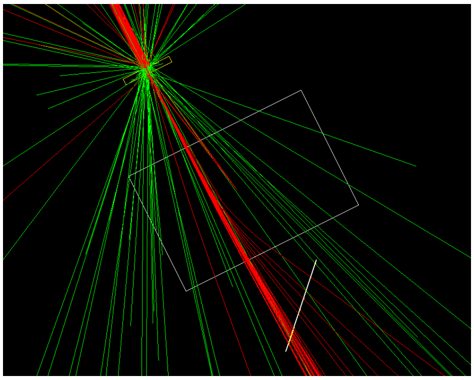

Figure 6: A plot from the Monte Carlo simulation with GEANT4. The electron beam is arriving from above impinging on the collimator. Grey rectangle in the middle indicates the magnetic field area. Particles are then registered on the tilted screen. Charged particles in the simulation are in red, neutral particles in green.

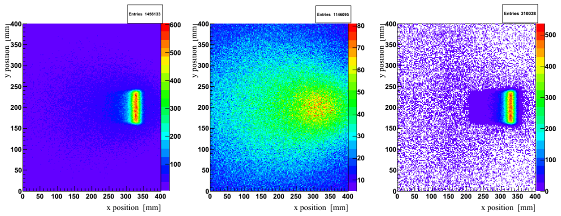

Figure 7: Simulated image on the fluorescent screen using 1.5mm slit and 30 cm long, 5mT dipole magnet. Left: all particles, middle: secondary particles, right: primary electrons only.

enough to fully stop the electron beam with the maximum energy achievable in the single CLIC structure i.e. about 20 MeV. A dipole magnet with an integrated field strength between 0.2-10 mTm will allow us to fully resolve almost the entire energy range from 0.5 to 20 MeV.

The energy resolution of the setup was estimated using true kinetic energy and the impact position on the screen, see Fig. 8, top. We divided the screen into slices and projected each slice in energy. A Gaussian function was fitted to each slice in order to estimate the energy spread, see Fig. 8, bottom. The expected energy resolution varies with the energies of the electrons, with 10% to 15% for the energies below 6 MeV, 15 to 25% below 12 MeV and reaching 30% for the energies above 15 MeV.

OUTLOOK

The 12 GHz stand-alone test-stand at CERN has been commissioned and is routinely operated to test the performance of the CLIC accelerating structures. The stand is equipped with standard RF diagnostics and two Faraday cups. We have designed and manufactured a magnetic spectrometer for research into breakdown physics. The spectrometer will be capable of measuring the spacial and

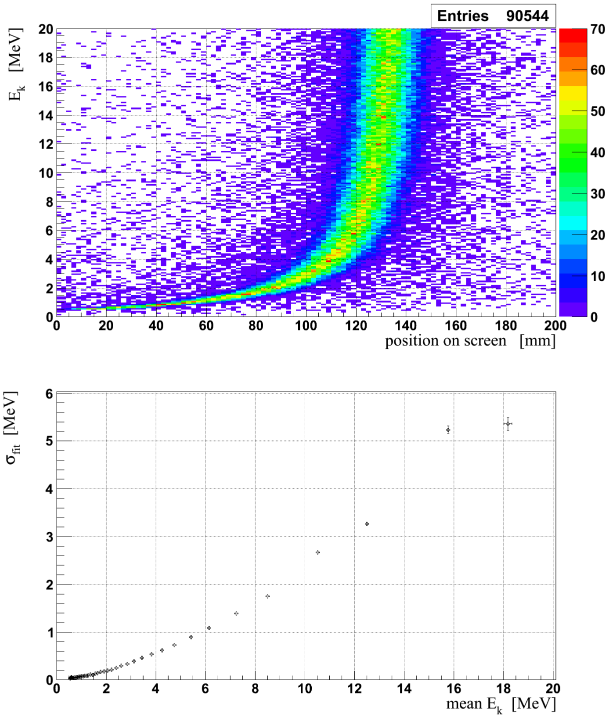

Figure 8: Top: Kinetic energy dependence on the position on the screen for a simulation with 5mm thick W collimator with 0.5 mm slit. Bottom: calculated energy spread.

the energy distribution of the charged particles ejected from the ACS and combined with RF power measurements will give a unique insight into vacuum breakdown phenomena. We plan to upgrade the test-stand with new diagnostics during Fall 2013.

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