GENERAL-PURPOSE SPECTROMETER FOR VACUUM BREAKDOWN DIAGNOSTICS FOR THE 12 GHZ TEST STAND AT CERN*

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Abstract

We discuss a spectrometer to analyze the electrons and ions ejected from a high-gradient CLIC accelerating structure that is installed in the klystron-driven 12 GHz test-stand at CERN. The charged particles escaping the structure provide useful information about the physics of the vacuum breakdown within a single RF pulse. The spectrometer consists of a dipole magnet, a pepper-pot collimator, a fluorescent screen and a fast camera. This enables us to detect both transverse parameters such as the emittance and longitudinal parameters such as the energy distribution of the ejected beams. We can correlate these measurements with e.g. the location of the breakdown inside the structure, by using information from the measured RF powers, giving in that way a complete picture of the vacuum breakdown phenomenon. The spectrometer was installed during Spring 2014 and will be commissioned during Summer 2014.

INTRODUCTION

The demand for high accelerating gradients was always present in the field of particle accelerators to keep the size and cost within reasonable limits. During the years a main focus has been to achieve higher accelerating gradients without compromising the reliability of the accelerator. However, the high gradients are possible by having extremely high electric field levels in the structures which, on the other hand, also cause problems with discharges that eventually limit the achievable gradients.

The knowledge of the physical processes inside the accelerating structure (ACS) during an RF pulse, and especially during breakdowns, is still limited. The theory aimed to understand the vacuum breakdown phenomena suggests that the electric field can be enhanced at some particular position (called emitters) on the wall of the cavity, most likely due to impurities or geometrical features. These positions are the source of primary field-emitted electrons observed 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 dark current.

High electric field and temperature effects at the emitters lead to the emission of not only electrons but also neutral molecules which are in turn ionized with the whole process leading to formation of plasma. When a high enough amount of free charges is present a breakdown occurs forming a vacuum arc. The arc becomes self-sustaining with rapidly increasing amount of free charges. Electrons in the plasma are accelerated in the RF field and removed. The mutual Coulomb repulsion of the remaining ions can lead to an "explosion" with the ions ejected outside the structure. This effect has been reported in [1].

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, detailed research on the mechanism and nature of these high voltage discharges is required.

The X-Band Test-Stands at CERN

The CLIC collaboration [2] early understood the need for a sufficient number of high-power tests of structures to validate the feasibility of the CLIC technology. This lead to the construction of a klystron-based stand-alone stand operated independently of the CLIC test facility. The test stand consist of a solid-state high-voltage modulator with 50 Hz repetition rate and a single 50 MW, 12 GHz klystron feeding the structure under test. The output pulse of the klystron is compressed using a pulse compressor with the peak power increased up to a factor of 2.7. Further details can be found in [3].

The ACS receives RF power from the klystron and the incident, reflected and transmitted power is measured at the directional couplers 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.

The Uppsala accelerator group has joined this effort with the intention to add advanced diagnostic capabilities to the CERN test stand [4]. For that purpose we have been developing a system with an external magnetic spectrometer for measurements of the spatial and energy distributions of the electrons emitted from the acceleration structure.

THE CONCEPT OF THE NEW DIAGNOSTICS

The schematic view of the spectrometer and the results of the simulations are shown on Fig. 1. The main idea is to pass the electrons emanating from the ACS through a collimator (in this example a pepper pot was simulated). The passing particles, defined by this pattern, form beamlets and continue further where they can be observe on e.g. a viewing screen. If a magnetic field is provided directly after the pepper-pot grid we can get an energy-dependent pattern on the screen behind the magnet. The viewing screen where the light spots

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are observed, is read out by a fast camera. 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. 5 we give an estimate of the energy resolution obtained that way.

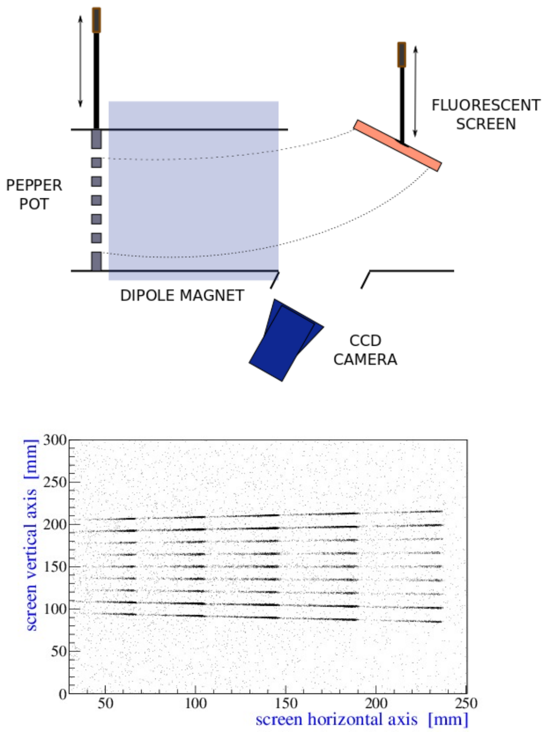

Figure 1: Top: Schematic view of the spectrometer function. Pepper-pot collimator is followed by a bending magnet and a fluorescent screen. Bottom: Simulated result observed on the screen. Each passing beamlet will form an energy dependent pattern on the screen.

THE DESIGN OF THE SPECTROMETER

The geometry and the pattern of the collimator has to be adapted to the expected width of the energy bands in order to avoid overlap of the beamlets. To allow for some flexibility of the system we have space for two collimator grids. The holder with the grids is fitted on a linear actuator which is operated by a stepper motor with possibility to choose any of the grids or to fully extract the grids from the beam, see Fig. 2. For the commissioning phase a simple 10x0.5 mm slit and a 0.5 mm diameter pin-hole were chosen. 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 through the magnet are registered on a 100x50x0.5 mm YAG:Ce fluorescent screen [5]. The screen plane forms a 30° angle with the beam axis in order to allow for a direct optical line to the camera at 90° angle. This way we avoid defocussing of the image due to depth-of-field of the camera system. A high quality mirror is used to reflect the image onto the CMOS sensor of a 2M pixels, 50fps camera which

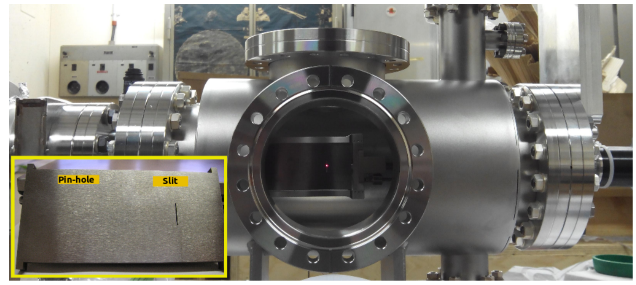

Figure 2: The vacuum chamber with the collimator frame mounted on the linear actuator. The collimators can be fully extracted from the particles' pathway. The insert in the corner shows the collimator with two separate 50x50mm patterns: a 0.5 mm diameter pin-hole and 0.5 mm slit.

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 a 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. Fig. 3 presents the whole setup.

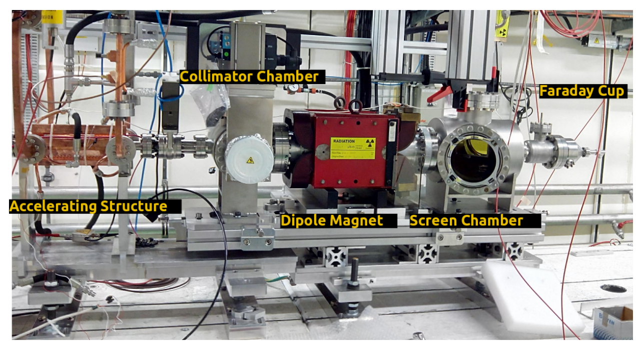

Figure 3: The new diagnostic setup during installation. From the left is shown the accelerating cavity followed by the first vacuum chamber housing the collimator, then dipole magnet and chamber with the fluorescent YAG screen with the view-port for the camera (the camera with the optical line is not in the picture). There is a special Faraday cup at the right side, that closes the setup.

A special Faraday cup is located in the forward direction. When both the screen and the collimator are removed it will collect the emitted charge and simultaneously will reflect the accompanied light emitted on the beam axis towards a radially mounted vacuum flange fitted with a light-guide to allow devices for optical spectroscopy to be attached. To achieve this, the front of the inner part of the Faraday cup has been cut at a 45° angle and polished to be highly reflective. Fig. 4 presents the photograph of the device.

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

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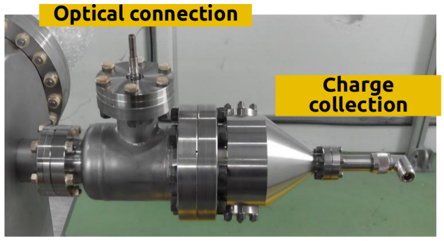

Figure 4: The Faraday cup at the end of the setup. The emitted electrons and ions with associated light come from the left side when both the collimator and the screen are extracted. The upper flange is fitted with a light-guide to allow optical devices to be attached.

passing the 10x0.5 mm slit. That is enough for spectroscopic analysis with the magnet.

The control and acquisition system has been developed in LabVIEW and will run on a desktop PC with a LabVIEW Real-Time system. Our system will be synchronized and triggered by breakdowns detected with the main conditioning software of the test stand.

GEANT4 Simulations

A simplified model of the diagnostic setup was implemented in GEANT4 [6] in order to optimize absorber material and thickness, magnet strength and the geometry of the setup. The model included a collimator with a slit or a pepper-pot, magnet and a detection screen. The secondary interactions and their effect on the background situation during image analysis were taken into account. 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. Based on the results from the simulation tungsten with 5 mm thickness was chosen as a material for the collimator to fully stop the electron beam. An integrated magnetic 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. 5, left. 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. 5, right. The expected energy resolution varies with the energies of

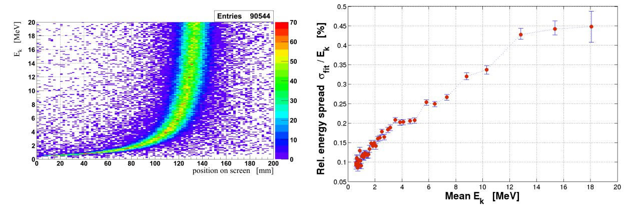

Figure 5: Left: Kinetic energy dependence on the position on the screen for a simulation with 5mm thick W collimator with 0.5 mm slit. Right: calculated energy spread.

the electrons, with 10% to 20% for the energies below 6 MeV, 20% to 35% below 12 MeV and reaching more than 40% 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. We have designed and manufactured a magnetic spectrometer for research into breakdown physics. The spectrometer will be capable of measuring the spacial and 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. The spectrometer is now installed in the test stand and awaits its restart after hardware upgrades done in the Spring 2014.

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REFERENCES

[1] M. Johnson, R. Ruber, V. Ziemann, H. Braun, “Arrival time measurements of ions accompanying RF breakdown”, Nucl. Inst. and Methods A 595 (2008) 568.

[2] "A Multi-TeV Linear Collider Based on CLIC Technology : CLIC Conceptual Design Report", *http://dx.doi.org/10.5170/CERN-2012-007*

[3] J. W. Kovermann *et al.*, “Commissioning of the First Klystron-based X-band Power Source at CERN”, Conf. Proc. C **1205201** (2012) 3428.

[4] M. Jacewicz *et al.*, "Instrumentation for the 12 GHz Stand-alone Test-stand to Test CLIC Acceleration Structures", Proceedings of the IPAC’11, **TUPC133** (2011) .

[5] CRYTUR, spol. s r.o., *http://www.crytur.cz/*

[6] S. Agostinelli *et al.*, "Geant4–a simulation toolkit", NIM A 506 (2003) 250-303