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SCUOLA DI SCIENZE DELLA NATURA

Corso di Laurea Magistrale in Fisica

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TESTING OF THE TD26 TYPE CAVITY UNDER BEAM LOADING FOR THE CLIC PROJECT

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Considerate la vostra semenza:
fatti non foste a viver come bruti,
ma per seguir virtute e canoscenza

Dante, *La Divina Commedia*
Canto XXVI

Abstract

(Leave this for the moment ....)

A new generation of colliders capable of reaching TeV energies is under development nowadays, and to succede in this task is necessary to show that the technology for such machine is available. The CLIC project is one of the most advanced design among the possible lepton colliders, and is formed by two normal conducting LINACs. To reach such high energies are necessary accelerating structures carrying gradient beyond 100MV/m and one of the biggest limitations is developing accelerating structures that present a sufficient low occurrence of vacuum arcs. This is pursued both with the design and the *conditioning*, which is the process of increasing the resilience to vacuum arcs of a structure using repetitive RF pulsing sessions.

The focus of this work is on the breakdown rate testing of the TD26 type cavity with and without beam presence inside. At CERN this test has been carried out on the cavity installed in the *dogleg* line in the CLIC-test-facility 3 (CTF3), and connected on the RF side to the X-band test stand 1 (Xbox1).

Other peculiar properties of the operation have been studied also, such has beam-induced RF generation into the cavity after the breakdowns, breakdown migration, ...

Italian abstract

(Translate once you have the ok to the english one)

Contents

Chapter 1

Introduction

Particle accelerators occupy a key role both in fundamental research and in all the applications and industrial processes that uses technology and processes developed initially for the elementary research.
A number of examples could be named among the spin-offs of accelerators' science, the most notable nowadays is the enormous progress of nanosciences in the last decade, that was made possible by the availability of high-brilliance light sources provided by synchrotrons, that was achievable thanks to the experience developed in the production of high quality electron beams. In the same way to inquire a much smaller scale are necessaries machines involving greater energies, and the development of the latter will lead the one of the former and so forth. Hence in this perspective keep developing the accelerators for the physical research is a fundamental requirement to assure that the cutting-edge technology of today turns into the "labware" of tomorrow for all the other sciences and the industry, in addition of the contribution that pursuing the fundamental research can give to our understanding of the world of the elementary particles.

Going back to the particle scale, at the moment the most successful model to explain the behaviour of the elementary particles is the *Standard Model*, but it's not conclusive and not able to answer to all the questions still open in particle Physics. A milestone in favour of the Standard Model was the observation of the Higgs Boson in 2012 [1, 2], and was made possible by the construction of the *Large Hadron Collider* at CERN[3]. However the full understanding of the physics at the particle scale still needs to be achieved. Partially this will be realised with the increase of the collision energy of the LHC, but also the International Committee for Future Accelerators (ICFA) consider that the results of LHC needs to be complemented by the results of a lepton collider in the TeV-range[4].

The reason of this decision is that according to the standard model the hadrons are particles composed by quarks, that are continously interacting exchanging gluons. This peculiarity cause the collision at high energy not to be between the hadrons themselves, but between partons composing them. In addition, there is no way to know in advance the energy of the partons involved, so it's not possible to know in advance which will be the energy of the collision. For example it is improbable for a parton in the 14 TeV centre-of-mass energy LHC to have much more than 1-2 TeV of energy at the interaction point[5]. On the other hand, the leptons are punctual particles, so the interaction is directly involving the two bullets themselves at a given energy, and the number of possible processes that can take place is definitely smaller.

This key difference in the behaviour of leptons and hadrons makes hadron colliders *machines for discovery*, because involve all the possible processes that can take place in a wide range of energies, and the lepton machines *machines for precision*, because the reduced number of possible processes guarantees the observation of the events of interest much easier.

1.1 Generalities on colliders

According to the beam use two kinds of accelerators can be distinguished:

1. Fixed target: where a beam is shoot against a non-moving target. The energy in the centre-of-mass is $E_{CM} = \sqrt{E_{BEAM}}$
2. Colliders: where two beams are accelerated in opposite directions and then made collide on each other. In this case the energy of the centre-of-mass is $E_{CM} = E_{BEAM1} + E_{BEAM2}$

therefore is easy to see that to reach a high centre-of-mass energy the collider topology is preferable.

Once the collision have taken place and got revealed, the rate of observation of a particular interaction process A is given by

$$\frac{dN(A)}{dt} = \mathscr{L}\,\sigma(A) \tag{1.1}$$

where σ is the process cross-section, which depends by the physics of the process A itself, and $\mathscr{L}$ is the luminosity, which depends entirely by the machine. Therefore the figure of merit when it comes to talk about accelerators is the luminosity, which is given by

$$\mathscr{L} = H_d \frac{N^2}{\sigma_x \sigma_y} n_b f_r \tag{1.2}$$

where N is the number of particles per bunch, σ_x and σ_y are the beam dimensions in the horizontal and vertical plane, n_b is the number of particle per bunch, f_r is the collision frequency of the bunches and H_d is a correction factor that takes in account the non ideality of the collision, such as crossing angle, collision offset, hour glass effect, non gaussian beam profile and so on.

Then becomes necessary try to reach the highest luminosity possible since the events that are going to be studied are rare. This is realised differently according to the design of the accelerating machine in use:

- linear accelerators (LINACs): present a low repetition frequency, typically lower than hundred of Hz and the beam is passing just once to be accelerated through the machine.
- circular accelerators (typically synchrotrons): have a higher repetition frequency, up to tenth of KHz, and are keeping the particle beam in orbit for many turns, so can accelerate it over a long period of time

After this distinction one could be led to think that the circular machine is the best choice in any case in order to reach high luminosity, but raising the energy of the beam a big issue comes out: the power loss in circular machines due to the emission of synchrotron radiation scales according to the following expression

$$P \propto \frac{1}{\rho^2}\frac{E^4}{m_0^4} \tag{1.3}$$

where ρ is the bending radius of the machine, E is the particle energy and m_0 is its rest mass. As can be noted in the table 1.1, the energy loss per turn is a relevant fraction of the beam energy, e.g. for the LEP machine over than 3 GeV were lost per turn, while the record energy per beam was 104.5 GeV. To raise the beam energy and reduce the energy loss, the radius of circular machines escalates quickly. Simply scaling LEP, it is possible to show that in order to reach the centre-of-mass energy of 3 TeV, the circumference should be increased to thousands of kilometers [6]. To solve the issue the development of new lepton colliders is so focusing on two different solutions:

1. Use muons instead of electrons: this innovative approach reduces the power lost because of the higher mass of the muon compared to the electron, but has to deal with the short life of muons, which is roughly $2\,\mu s$ in the laboratory frame
2. Limit the losses caused by synchrotron radiation, or increasing the bending radius or abandon the circular topology for the linear one

Also has to be noted that the former technology is rather new and needs to still be fully developed, while the latter profits of the progresses achieved in the last half century mainly in SLAC and KEK on the LINAC technology.

In this perspective a number of project are under study at the moment, of wich the most ambitious are FCC-ee, *Future Circular Collider*, ILC, *International Linear Collider*, and CLIC, *Compact Linear Collider*. The first one consist in a circular collider which is supposed to be placed in a 80-100 km long tunnel before of the installation of the FCC-hh, the other are LINACs even if based on completely different technologies and solutions. A comparison of the features of these projects in the final stage is presented in the table 1.1, and also LEP is presented as example of circular lepton collider.

Furthermore a recent interest arose on more compact technologies, e.g. plasma acceleration techniques, but the reliability of such designs still need to be proven in the perspective of creating a fully functional machine that goes beyond the demonstration of the working physical principle.

Parameter	**LEP2**	**FCC-ee**	**CLIC**		**ILC**
$\sqrt{s}\,[GeV]$	209	350	500	3000	500
$\mathscr{L}_{peak}\;[10^{34}\,cm^{-2}\,s^{-1}]$	0.012	1.3	2.3	5.9	1.8
Total lenght $[km]$	26.7	100	13	48.4	31
Loaded acc. gradient $[MV/m]$			80	100	31.5
Bunch population $[10^9]$	105	170	6.8	3.72	500
Bunch spacing $[ns]$		4000	0.5	0.5	554
Collision rate $[Hz]$			50	50	5
$\epsilon_x^* \,/\, \epsilon_y^*\,[\mu m]/[nm]$			2.4/25	0.66/20	10/35
$\sigma_x^* \,/\, \sigma_y^*\,[nm]$		3600/70	202/2.3	40/1	474/5.9
Energy loss per turn $[GeV]$	3.34	7.55	-	-	-
Power consumption $[MW]$	3.34	7.55			163

Table 1.1: Comparison of two circular machines, LEP[7] and FCC-ee[7, 8] and the two projects for linear machines, the fist and last stage of the CLIC implementation [9] and the final stage of ILC[10]

1.2 The CLIC project and the CTF3 facility

The *Compact Linear Collider* is the project for a linear electron-positron collider capable of reaching a centre-of-mass collision energy of 3 TeV and a luminosity of 2x10$^{34}\,cm^{-2}\,s^{-1}$ in the final stage.

The realisation of such machine implies many technological challenges in order to keep the power consumption and the dimension limited while matching the design goal parameters. These challenges have been faced developing the novel *two-beam acceleration scheme*, in which the idea is to use a high-current and low-energy beam, the *Drive Beam*, in order to generate the RF power to accelerate a low-current and high-energy beam used for the experiments, named *Main Beam.*

The Drive Beam is produced using a dedicated LINAC, and then the current is multiplied using a delay loop and two recombination rings, reaching a combination factor of 2x3x4 = 24. This topology generates the beam with a final frequency of the bunches of 12 GHz, and the reason for this kind of implementation is to reach the highest possible efficiency in the Drive Beam production, in order to shrink the power consumption to the smallest possible. To reach this goal the acceleration in the LINAC is performed using the accelerating cavities in fully-loaded mode.

While the biggest challenge for the main beam is reaching the necessary high current, for the Main Beam the hardest challenge is generating a beam with the smallest dimension possible, in order to increase the luminosity of the machine as much as possible.

The Main Beam is produced in a separate facility, where a DC-photo gun system provides the initial polarised electron beam, and afterwards part of the beam is sent to a target in order to generate the positron beam. Once both the beams have been produced, they are sent to the next accelerating stages, which are composed of LINACs to raise the beam's energy and of damping rings to reduce the emittances.

The detailed description of the Main Beam production and the Drive Beam recombination process can be found in [9] and about how the working principle have been demonstrated in the CTF3 in [11].

Once both beams have been produced, are sent to the common tunnel where the Two-beams modules are installed. The Two-beam module is composed by two principal sections, which are the PETS, *Power Extraction and Transfer Structures*, and the accelerating structures for the Main Beam, as exploited in figure 1.2. The Main Beam passes through the PETS and gets decelerated. As product of the deceleration a pulse of RF power is produced, which is transferred by a waveguide network and used to accelerate the Main Beam. In this way it is possible to reach an efficient acceleration of the Main Beam up to the desired energy for the experiments

1.2.1 Physics and staging

The machine is designed to be built in 3 stages, with a final energy of 3 TeV.

Since the CDR[9] was released just before the discovery of the Higgs boson, the centre of mass energy stages have been reshaped in order to be able to access to interesting measurements, anyway for a given centre-of-mass energy, the energy can be modified by a third with limited loss of performance[12], allowing an eventual retuning of the energy of the stages following the results of the last LHC physics campaign.

The energy staging have been chosen as follows, further informations can be found in[13, 14], but the leading idea is to make accessible the Higgs and top physics from the first stage.

The first stage is proposed to be 380 GeV, and it gives access to the Standard model Higgs physics and top-quark physics. The measurements on the former can be conducted through Higgsstrahlung and WW-fusion processes, thereby providing accurate model-indipendent measurements of Higgs couplings to bosons and fermions[15]; the latter measurements will be focused on the $t\bar{t}$ pair production threshold in the vicinity of $\sqrt{s} = 350$ GeV.

The second stage is proposed at 1.5 TeV and allows to access new physics phenomena and additional properties of the Higgs boson and the top quark, such as Higgs self-coupling and rare Higgs branching ratios.

The third stage is proposed at 3 TeV and will give direct access to pair-produced particles with mass up to 1.5 TeV or single particles with mass up to 3 TeV. This stage is particularly interesting as test for the BSM theories, since such high energy in a lepton machine makes the observation of new particles much easier than in the LHC.

A further remodulation of these steps is possible after the publication of the results of the run 2 of the LHC, but anyway the advantage of a linear machine in this sense is that the final energy can be reshaped modifying the total length of the machine. In figure 1.3 is shown the track of a possible CLIC

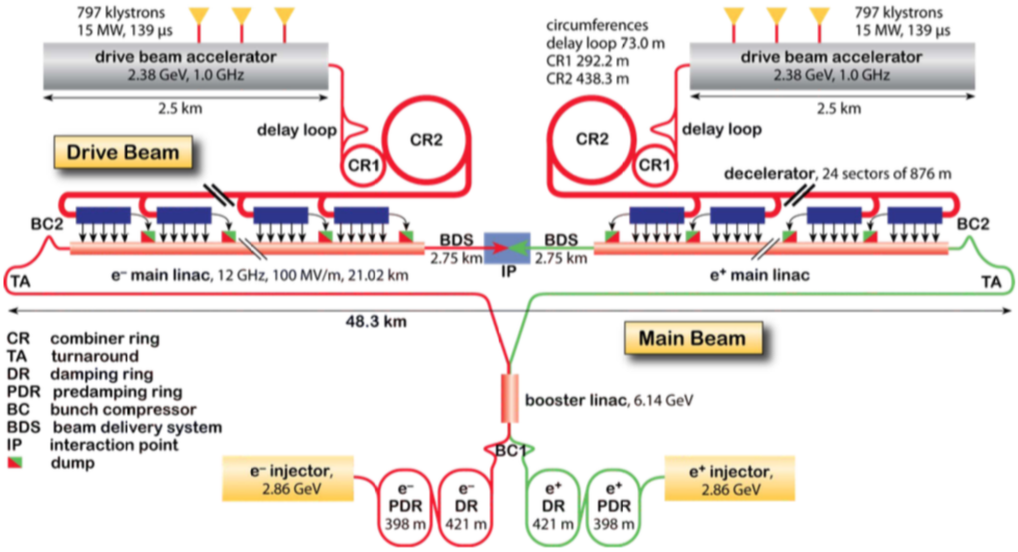

Figure 1.1: Layout of the final stage of CLIC

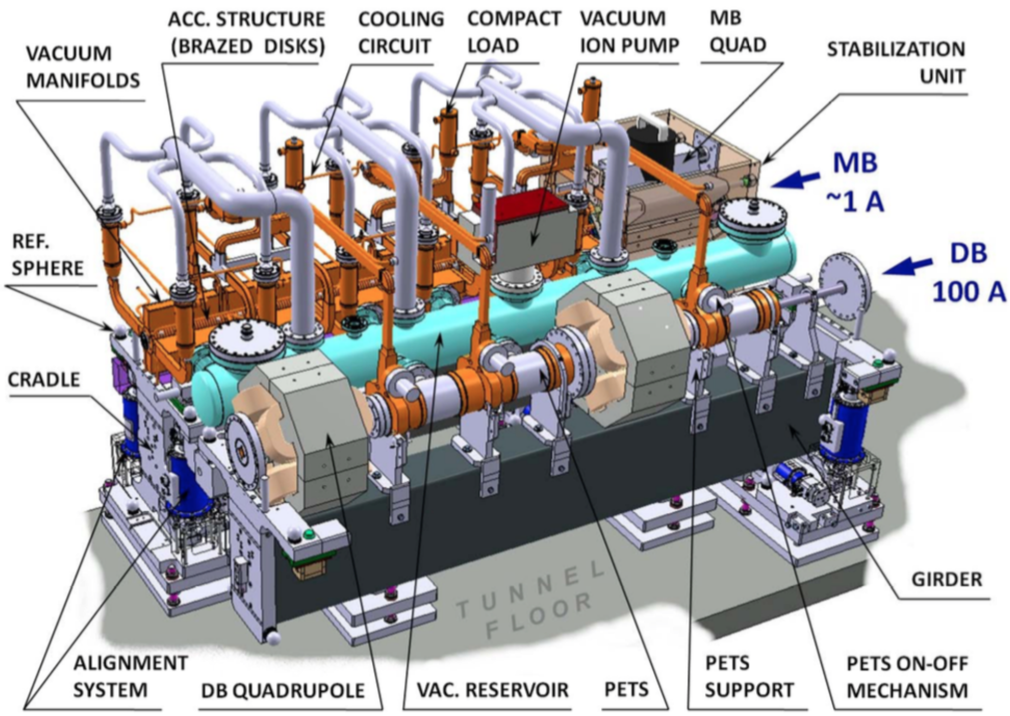

Figure 1.2: Design of a Two-beam module.

build in the Geneva area, in order to give an idea about the order of magnitude of that kind of facility compared to LHC and SPS.

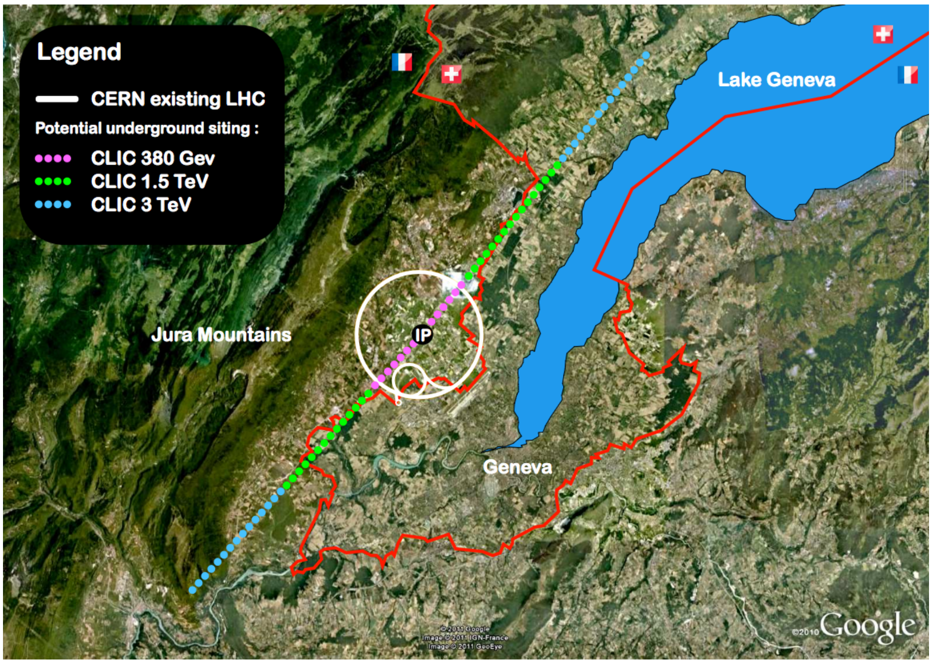

Figure 1.3: Map of the CLIC facility, if implemented in the Geneva area

1.2.2 Main parameters and main issues

There are many issues that can affect the performance of a machine like CLIC, and need to be analysed carefully since no similar machine have been built so far. The main issues are:

1. 100 MV/m accelerating gradient: this requirement comes from the final energy of 3 TeV and the requirement of a maximum length of 50 km
2. Breakdown rate $< 3\text{x}10^{-7}$ breakdowns per pulse per meter: this limitation comes from the limit on design luminosity loss in case of breakdown. Is the aim of this work and will be stressed in detail later
3. Transverse wakefields limitation: wakefields have to be considered because of the short bunch spacing in the bunch train. If not limited are a serious issue to the luminosity.
4. Powering the accelerating structures: no klystrons on the market are able to produce high power pulses 150-200 ns long. This requires the use of pulse compression systems or the two-beam acceleration scheme, that have never built and operated so far in a functional collider
5. Generate the drive beam with an efficiency of 97% in order to contain the power consumption. Also the efficiency of the power transfer between the beams is a key issue in order to reach the energy goal

6. Extremely small beam emittance and size: in order to match the luminosity goal with the typical low repetition rate of a LINAC is necessary to squeeze the beam as much as possible, reaching the goal of 40 and 1 nm at the interaction point in the horizontal and vertical plane. This parameter includes the realisation of a nanometric alignment and vibration containing system

Therefore the parameters in the table 1.2 have been selected in order to match the design parameters reported in the table 1.1 for the top design energy.

Description	**CLIC 3 TeV**
Peak luminosity $[cm^{-2}s^{-1}]$	2.0x10^{34}
Total site length $[km]$	48.4
Loaded accelerating gradient $[MV/m]$	100
Main LINAC RF frequency $[GHz]$	12
Charge per bunch $[nC]$	3.7x10^{9}
Bunch separation $[ns]$	0.5
Bunches per train	312
Beam pulse duration $[ns]$	156
ϵ_x^* / ϵ_y^* $[\mu m]/[nm]$	0.66/20
σ_x^* / σ_y^* $[nm]$	40/1

Table 1.2: CLIC main parameters in the final stage

1.2.3 The CLIC Test Facility 3

To be able to assert that the CLIC scheme is a feasible and reliable technology to build a functional collider, a number of tests have to be conduced since no accelerators using the Two-beam acceleration concept have been reached the production phase yet. To satisfy this requirement at CERN have been realised the CLIC Test Facility, that is in charge of demonstrate experimentally:

- The feasibility of the Drive Beam generation with a frequency of 12 GHz, performing the beam recobination using a delay loop and a combiner ring for a total multiplication factor of $2 \times 4 = 8$
- The RF power production using the PETS and investigate the possible issues of the Two-beam scheme

In addition a branch of the LINAC was used to perform high-gradient tests with the beam presence inside the accelerating cavity, which is the topic of the following work.

Chapter 2

Accelerating structures

2.1 Accelerating structures

2.1.1 Elements of electromagnetism

Maxwell's equations in a medium

It's well known since the basic courses of physics that the electromagnetic waves follow the Maxwell's equations, that in a medium are

$$\begin{array}{ll} \nabla.\vec{D} = \rho_{free} & \nabla.\vec{B} = 0 \\ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} & \nabla \times \vec{H} = \vec{J}_{cond} + \frac{\partial \vec{D}}{\partial t} \end{array} \tag{2.1}$$

where $\vec{D} = \epsilon\vec{E}$, $\vec{B} = \mu\vec{H}$ and $\vec{E} = \sigma\vec{J}$ (the full derivation and further details on the notation are available in any book on classical electromagnetism, such as [16, 17]). The propagation in vacuum is described by the same equations and can be easily derived from the (2.1) with the choice of the appropriate constants.

Confined propagation of EM waves

In some particular cases the confined propagation of electromagnetic waves is possible, and realised using a metal waveguide to lead all the energy in a single direction. In this section some useful results on the propagation in a waveguide will be stressed.

Using the set of equation (2.1) and asking that the electric field is normal to the surface to avoid power dissipation due to the Joule effect (so $\vec{E} \times \vec{n} = 0$), it can be derived the set of admitted solutions for the propagation of the EM waves. Among the solutions, the most important are the *Transverse Magnetic* solutions (T.M.), where the axial component of the magnetic field is null, and the *Transverse Electric* solutions (T.E.), which is the same for the electric field.

Particle acceleration

[?]

2.1.2 Periodic structures and synchronous acceleration

In order to deliver a constant energy gain to a charged particle two conditions have to be met:

1. The electromagnetic wave has to have a non-zero component in the direction of the motion of the particle

2. The phase velocity of a wave have to be the same of the particle velocity, in order to keep the relative phase constant, and so the acceleration

using some results of the theory of EM waves it is possible to derive that the former cannot be accomplished in the free space, but can be easily met in a cavity (e.g. a waveguide), and to satisfy the latter is not sufficient simply using a waveguide, but is necessary a particular geometry, typically periodic geometries are used for this purpose.

[16]

2.1.3 Constant gradient vs constant impedance structures

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2.1.4 Beam effect on the accelerating structure

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2.1.5 TD26 structures for the Main Beam of CLIC

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2.2 High power limits and scaling laws

The limiting factors for room-temperature high-gradient accelerators have been identified as *field emission* and *RF breakdown.* The former is the emission of electrons in the form of the so called *"Dark current"*, that subtracts RF power, causes radiation and can produce wakefields; the latter is a limiting factor to the operation of accelerators and can damage the structures.[18]

The understanding of these phenomena is particularly challenging and requires a mixture of notions of disciplines such as surface physics, metallurgy, fabrication processes, microwaves, beam dynamic and plasma physics. At the moment a satisfactory unified theory of the processes that take place during the breakdowns have not been found yet, then the improvement of the structures is achieved using some scaling laws for the high power limitations, that have been deducted from the experience and the experiments on the structures tested so far.

2.2.1 Field emission law

Emission from flat clean surface

The field emission law was theorised by Fowler and Nordheim in 1928 and rule the current emission from a metal with applied an intense electric field. The derivation was carried on calculating the tunnel probability of electrons of the conduction band through the perfectly flat and clean surface of a metal.
The applied electric field modify the potential barrier, and the current density of emitted electrons can be derived as the following, giving the *Fowler-Nordheim equation* [19]

$$J_F = \frac{1.54 \times 10^{-6} \times 10^{4.52\phi^{-0.5}} E^2}{\phi} \exp\left(-\frac{6.53 \times 10^9 \phi^{1.5}}{E}\right) \quad [A.m^{-2}] \tag{2.1}$$

where ϕ is the work function of the material and E is the applied electric field.

Enhanced field emission

It's well known that almost any surface is never perfectly clean and flat, and also the fact that the asperities of the surface provoke an enhancement of the local electric field. This behaviour lead to the phenomenon known as *Enhanced Field Emission* (EFE), which major contributors are:

- Surface imperfection due to imperfect machining

- Metallic dust
- Molten craters after breakdowns
- Absorbed gas

and some others. These effects can create particular sites known as "emitters". It's a common praxis define the field enhancement factor β to relate the electric field to the microscopic one

$$E_m = \beta E \tag{2.2}$$

and the β factors can be calculated according to the emitter's geometry [20] as exploited in figure 2.1. Once the local field is known, using the formula 2.1 calculate the current emitted from EFE by an emitter site of area A gives

$$I_F = \frac{1.54 \times 10^{-6} \times 10^{4.52\phi^{-0.5}} A\beta^2 E^2}{\phi} \exp\left(-\frac{6.53 \times 10^9 \phi^{1.5}}{\beta E}\right) \quad [A] \tag{2.3}$$

where βE is the local field, ϕ is the work function of the material and A the area of the considered emitter.

In the RF case the average current emitted is given by similar calculations, averaging the electric field on an RF period. The full calculation is stressed in [18].

Experimental evidence of the dark current emission have been detected by setups equipped with Faraday Cups, as in [21].

The emission of dark current seems to be a precursor of the breakdown process, even if the relationship between the two processes has not been clarified so far.

2.2.2 Kilpatrick's critereon

The Kilpatrick's Critereon was the first attempt to create a high power limit valid both in DC and RF applications [22]. The model was based on the acknowledgement of the Field Emission, and suggesting that the vacuum arc was created by the cascade of secondary electrons ejected from the surface by ion bombardment.

Using data collected in the 1950's, the following empirical law was formulated

$$WE^2 \text{exp}\left(-1.7 \times 10^5 E^{-1}\right) = 1.8 \times 10^{14} \tag{2.4}$$

where W is the maximum possible ion energy in eV, and E is the field in V/m. This can also be rewritten in the case of the RF to give a frequency limit, as

$$f = 1.64\ E^2 \ \exp\left(-\frac{8.5}{E}\right) \tag{2.5}$$

where f is the frequency in MHz and E is the electric field in MV/m.

The critereon was reviewed many times up to now, because the experiments conducted nowadays show a limit up to 10 times lower than Kilpatrick's prediction, and this can be addressed to different reasons: first of all the quality of

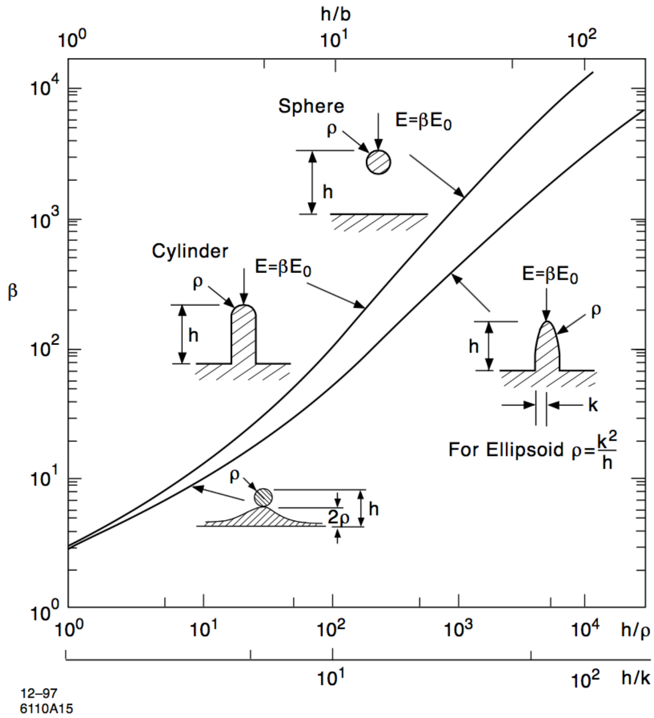

Figure 2.1: Field enhancement factors for simple geometries of metallic protrusions, plotted as function of geometrical features. From [20]

the machining of the structures have increased considerably since the 1950's; in second instance the formula for W was deducted for parallel plates, but the condition inside the RF cavities are different during operations; and finally the key assumption was that the breakdown was triggered by the secondary emission provoked by the ion bombardment.

At the end of the 1980's J.D.Wang finally proposed a model based on microprotrusion effect on the field and field emission, that involves the formation of a micro-plasma during the breakdown process. Also the Kilpatrick's limit was revised again in order to match the experimental results. [23, 24]

2.2.3 The modified Poynting vector S_c

Different other scalings have been proposed so far involving power flow, such as P/C scaling (related to the maximum surface electrical field) or a more advanced one [25], but even the last one showed some deviations from expectations in part of the structures tested and is applicable just to travelling wave structures (TWS) since in standing wave structures (SWS) the power flow is close to zero.

During the work on high gradient normal conducting accelerating structures for the CLIC project, was however developed a new field quantity, the *Modified Poynting Vector* S_c, that is suitable both for TWS and SWS. [26]

The founding of this

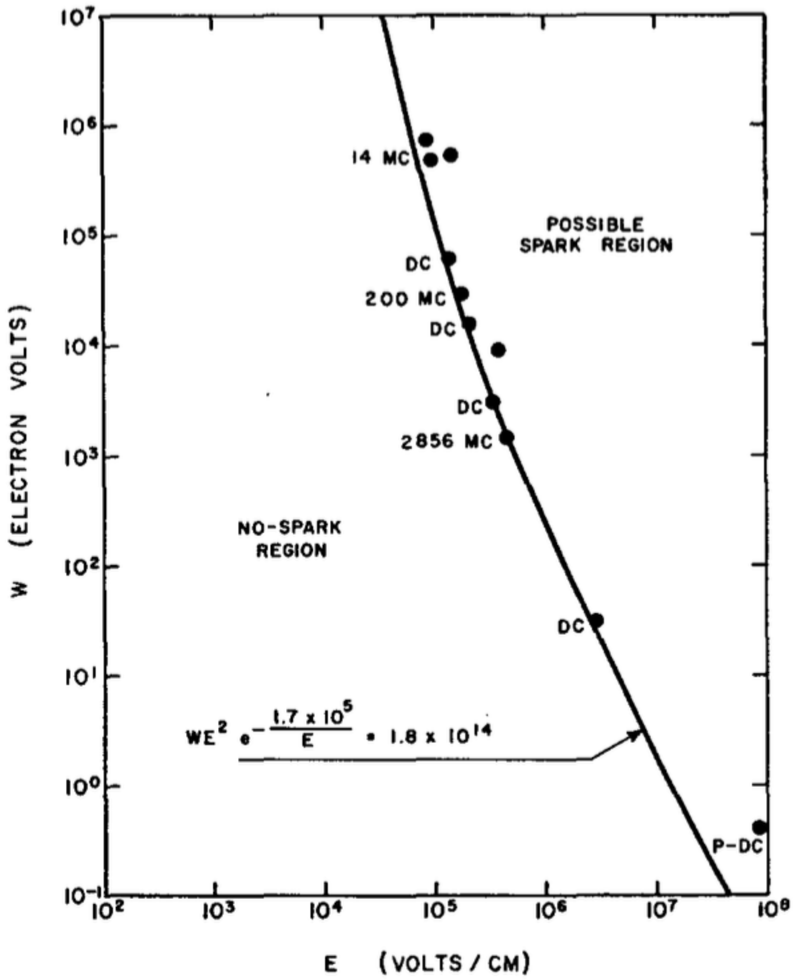

Figure 2.2: Kilpatrick's original plot. Note that $MC = MHz$ (*Mega Cycles*) and that W for RF is function of frequency, voltage and gap amplitude. See paper for details [22]

are that: the breakdown process is a determined by the accumulation of the pulses rather than the single pulse and the possible triggers of the breakdown can be induced by many processes that will be discussed later and are not relevant for the scaling law derivation.

A number of effects have to be taken into account (a simple geometry is considered, a cilindrical protrusion surmounted by a emispherical cap):

Pulsed heating by field emission current

it's known that the field emission gets enhanced by the presence of the protrusion as described before, and in this case the field enhancement factor can be expressed as $\beta \simeq h/r$, where h is the tip height and r is the cap radius. So the tip will emit a current according to the Fowler-Nordheim law, causing in first approximation the heating of the tip due to the ohmic heating. Assuming that the edge of the tip will be the most heated part, and using the heat conduction equation, it is possible to derive the emitted current to bring the tip to the melted state, which is found to be approximately $36\,A/\mu m^2$ for a tip of $1\,\mu m$ height and a pulse of $100\,ns$. This is consistent with the findings in [27]. The β factor can be then derived, which is approximately between 40 and 60 considering a surface electric field in case of breakdown between 200 and 300 MV/m.

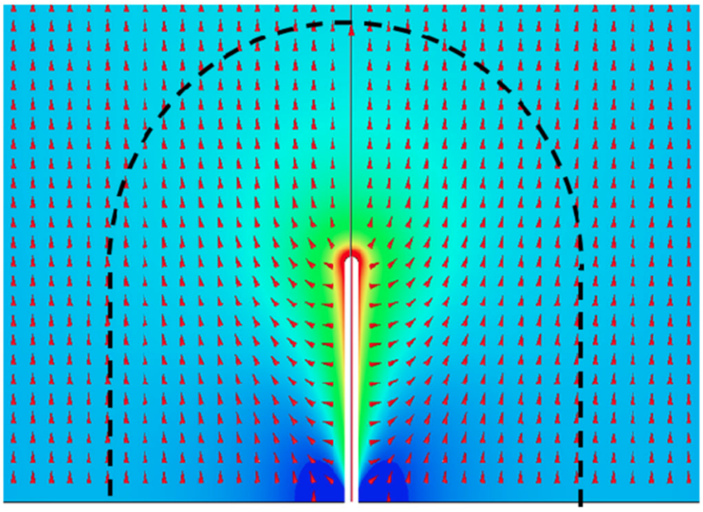

Figure 2.3: Electric field distribution around the protrusion considered. Arrows indicate the direction of the field and the color code the absolute value of the field, mapped logarithmically [26]

Power flow near an emission site

The heating of the tip mentioned before requires a huge amount of energy, which can be supplied only by the RF power present into the cavity. This is described by the Poynting vector $S_{RF} = E \times H_{RF}$. As discussed before a current is established in the tip, and flows through, subtracting energy to the EM field in the surroundings of the tip; the current flows through the tip and leave it at the edge, getting sprayed in the cavity according to the Fowler-Nordheim theory. Since any current flowing creates an associated magnetic field, the power flow due to the emission is given by $S_{FN} = E \times H_{FN}$.

The key point is that since the copper is a very good conductor, so to provoke a notable ohmic heating of the tip, a significant power flow through the tip is necessary. This can be calculated evaluating the S_{FN} at a distance $d = h$ from the edge of the tip, where the electric field is not perturbed anymore by the shape of the tip itself. This can be formulated as the condition

$$P_{RF} \geq P_{FN} \gg P_{loss} \tag{2.6}$$

where P_{loss} is the power lost for ohmic heating and P_{FN} the power flow through the tip.

Considering now the relative phase of the P_{RF} and of the P_{FN} it is possible to derive an expression for the power emitted in a copper cavity

$$P_{FN}(t) = A\, E_0^3\, sin^3\omega t\ exp\left(\frac{-62}{\beta E_0\, sin\,\omega t}\right) \tag{2.7}$$

where the work function for the copper have been used is $\phi = 4.5\, eV$, A is the area of the conductor and $\omega = 2\pi f$ is the angular velocity.

The RF power can be divided in real and imaginary part, with a phase shift of 90°. The real part is the energy propagating into the structure only and the imaginary part is the energy stored in the cavity both magnetically or electrically as happens in every resonant cavity. Since the active power flow is more efficient than the reactive one in providing power for the field emission, a weighting factor g_c is introduced. Also for practice reasons since all the simulation codes work using the complex Poynting vector $\bar{S}$, the precedent reasoning can be adapted to meet the custom, using the *Modified Poynting Vector*

$$S_c = Re\{\bar{S}\} + g_c\, Im\{\bar{S}\} \qquad [W/\mu m^2] \tag{2.8}$$

Since this quantity can be calculated in any point of a structure, this allows to identify in advance the regions which are more sensible to the breakdown process. The rule of thumb given by the current experience says that this quantity should not exceed the value of $5W/\mu m^2$ to have a breakdown rate smaller than $1 \times 10^{-6}\, bpp\, m^{-1}$ with a pulse length of 200 ns.

This quantity have been used successfully to design all the last generations of CLIC structures, including the one tested in this work.

Chapter 3

The breakdown process

3.1 phase1

3.2 phase2

3.3 phase3

Enumeration example

Chapter 4

Experimental setup

4.1 The TD26 accelerating structure

4.2 The LINAC and the Dogleg

Bullet list example

- first point
- second point
- third point

4.3 RF power generation

Enumeration example

1. first point
2. second point
3. third point

Description example

first descr first point

second descr second point

third descr third point

4.4 DAQ system

4.4.1 Hardware

4.4.2 Online triggers

describe the online, but then the offline is in the next chapter
. . . but you can also build nested lists

- first point
  - first point
  - second point
- second point
- third point

4.5 Other systems

mention here thermal systems for the structure and something else ???

Chapter 5

Data analysis tools

5.1 Offline selection of the events

A tabular example

Tit1	Tit2
el1	el2
el1	el2
el1	el2

but tabulars cannot be captioned ! (are in text elements)

Using the table environment, the caption works ! BUT BECOMES FLOATING OBJECTS (in fact is on the bottom of the page due to no more text inserted afterwards).

Same thing for the figure environment

5.2 Time and space positioning of the breakdowns

5.3 Migration of the breakdowns

5.4 Beam induced RF

5.5 Neural network based events selection

1	2	3
4	5	6
7	8	9

Table 5.1: A simple table

Chapter 6

Results and future developments

6.1 Results

A figure example, with text in line (NO CAPTION)

A figure example, with floating object and caption

6.2 Further developments

Figure 6.1: the logo of UniTo

List of abbreviations

BSM	Beyond Standard Model
CDR	Conceptual Design Report
CERN	Conseil européen pour la Recherche nucléaire, Geneva, Switzerland
CLIC	Compact Linear Collider
CTF3	CLIC test facility 3
EFE	Enhanced Field Emission
EM	Electromagnetism *-or-* electromagnetic
FCC-ee	Future Circular Collider, lepton version
FCC-hh	Future Circular Collider, hadron version
ICFA	International Committee for Future Accelerators
ILC	International Linear Collider
KEK	High Energy Accelerator Research Organization, Tsukuba, Japan
LEP	Large Electron Positron Collider
LHC	Large Hadron Collider
LINAC	Linear Accelerator
PETS	Power Extraction and Transfer Structure
RF	Radio frequency
SLAC	Stanford Linear Accelerator, Menlo Park, California
SM	Standard Model
SPS	Super Proton Synchrotron
SWS	Standing Wave Structure
TBM	Two-Beams module
TDR	Technical Design Report
TWS	Travelling Wave Structure
XBOX	X-band high power RF test stand

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