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RADIATION TRIGGERED BREAKDOWN PHENOMENA IN HIGH ENERGY e⁺ e⁻ COLLIDERS

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Abstract

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Radiation Triggered Breakdown Phenomena in High Energy $e^+ e^-$ Colliders

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Abstract

The presence of radiation in a high voltage system under ultra high vacuum can increase the frequency of breakdown phenomena by orders of magnitude. One type of radiation consists of electromagnetic waves (Laser and UV light, synchrotron light, X-rays, γ -rays). The second type comprises charged particles and ions. Both types of radiation are found abundantly in high energy $e^+ e^-$ colliders. To study the particular effect of an isolated radiation source in this environment is difficult and limited by many restrictions. Thus, the principle strategy is not directed towards understanding and improving the breakdown characteristics of high AC or DC field equipment, but rather towards reducing the radiation flux incident on the critical devices. This can be achieved either by absorbing the radiation or by trapping the charged particles. However, in the case of the 'pretzel' separation project for the Large Electron Positron (LEP) collider this strategy failed; as a result many experiments have been carried out in order to achieve a better understanding of radiation triggered breakdown phenomena. Observations made in some other $e^+ e^-$ colliders are also reported and compared with the LEP results.

1 Introduction

Radiation triggered breakdown phenomena occurring in the different types of electrostatic separators of the Large Electron Positron (LEP) collider at CERN are discussed in detail. The separators, which are equipped with electrodes several meters in length mounted in an ultra-high vacuum tank, are operated at a field strength of around 2 MV/m across a gap of about 10 cm.

The documentation of radiation triggered breakdown phenomena in other $e^+ e^-$ accelerators is rather scarce, but a few examples will be presented from CESR, TRISTAN, and SPS.

LEP is a 26.6 km circumference $e^+ e^-$ storage ring [1] which presently operates with 4 bunches per beam in a possible energy range from 20 to 55 GeV. LEP produced the first collisions in August 1989 and at present the main aim is to produce Z^0 particles at 45.6 GeV for the four LEP experiments. The total number of Z^0 had exceeded 2 million by the end of 1991 [2].

Electrostatic separators are used to separate the 4 e^+ from the 4 e^- bunches at the eight encounters from injection at 20 GeV up to the top energy [3]. Since the beam-beam force for colliding beams which limits the beam current is inversely proportional to the cube of the energy, such a separation of the bunches at the points of encounter allows the accumulation of much higher currents in LEP. After acceleration to the Z^0 energy the beams are brought into collision in the centres of the four LEP experiments. The separation of the bunches at the other four encounters is maintained. The high voltage performance of this separation system, comprising 32 electrostatic separators of vertical deflection (ZL), is described in chapter 5. It is mainly characterized by the electric breakdown rate which, with beam, is at least one order of magnitude higher than without beam.

A brief review is given in chapter 2 of the basic physics of the electromagnetic interactions of the beam important for the LEP and similar high energy $e^+ e^-$ colliders. The mechanism for breakdown processes without and with radiation are discussed in chapters 3 and 4, respectively.

The future goals of LEP are to further increase the Z^0 production rate by doubling the number of bunches to 8 e^+ and 8 e^- , starting from October of this year, and to increase the beam energy in 1994 to around 90 GeV by the addition of around 200 superconducting cavities. For the latter project another 8 vertical separators (ZL) are now under construction.

	CESR	SPS	TRISTAN	LEP
Energy (GeV)	5.3	20	29	46
Circumference (m)	768	6911	3018	26658
Bending radius (m)	88	741	246.5	3096
Bunches per beam	7	4	2	4
Total current (mA)	200	1	14.5	3.7
Synchrotron loss/turn (MeV)	1.04	19.1	254	126
Critical energy (keV)	3.7	23.9	44.6	69.7
Power loss (kW)	208	19.1	3.7	473

Table 1: Main parameters of some high energy accelerators or colliders

For the doubling of the number of bunches, we have implemented a 'pretzel' separation scheme which permits the separation of the bunches at the 8 additional encounters [4, 5]. The performance of this new separation system, comprising 8 electrostatic separators (ZX) of horizontal deflection and different construction with respect to the initial system (ZL), is described in chapter 6. In particular the studies made on radiation triggered breakdown are reported.

2 Some physics of the beam interactions in high energy $e^+ e^-$ colliders

The most important phenomenon is the production of synchrotron radiation in the strong magnetic dipole field which bends the beams onto circular orbits.

The interaction of the beam particles and high energy photons with matter (e.g. the vacuum chamber wall) predominantly creates a type of radiation called an electromagnetic shower.

2.1 Synchrotron radiation

Synchrotron radiation (SR) is produced when relativistic electrons or positrons with an energy $E \gg E_o = mc^2$ are deflected in a strong magnetic field. Radiation is emitted tangentially to the orbit and is spatially confined to a small angle $\theta \approx \gamma^{-1} = E_o/E$, typically less than 1 mrad for energies above 1 GeV. The spectrum is continuous, passing through the millimeter wave length, the infra red, optical, UV and into

the X-ray region. The number of quanta per unit band width gradually decreases with the photon energy ϵ as $\epsilon^{-2/3}$ up to the critical energy ϵ_c , where the spectrum is rapidly terminated. In an isomagnetic collider like LEP where the bending radius ρ (m) is constant or zero, the energy loss per turn is given by:

$$\Delta E = 88.46 E^4 / \rho \text{ (keV)}$$

with the beam energy E measured in GeV. The total power loss of a circulating electron current I (mA) becomes:

$$P_\gamma = \Delta E I \text{ (W)}$$

The critical photon energy ϵ_c is the energy which divides the power spectrum into two equal parts and is given by:

$$\epsilon_c = 2.218 E^3 / \rho \text{ (keV)}$$

The total photon flux when passing through a magnet of length l is given approximately by:

$$dN/dt \simeq 1.6 \cdot 10^{17} E I l / \rho$$

The main parameters relevant to the synchrotron radiation characteristics are listed in Table 1 for the accelerators and colliders discussed here.

2.2 Interaction of beam particles and photons with matter

These interactions occur because of the electromagnetic fields carried by the particles and target matter. Interactions between an atom and an electron, positron, or photon can be grouped into three classes according to the nearest approach of the 'projectile' orbit from the centre of the atom, characterized by the impact parameter b ; this leads to the classification shown in table 2 [6].

1. $b > \text{atomic radius}$: Atom as a whole acts as a single entity.
2. $b \approx \text{atomic radius}$: Interaction with individual shell electrons.
3. $b < \text{atomic radius}$: Deflection of 'projectiles' in the electromagnetic field of the nucleus; this is the most important effect for high energy particles. The reason for the phenomenon of the electromagnetic shower or cascade is that the mean-free-path of electrons (positrons) due to bremsstrahlung is of the same order as the mean-free-path of photons due to pair production. Such a cascade can be built up when e.g. high energy e^+ or e^- hit the LEP vacuum chamber. Obviously many of the low energy

Interaction with	Electrons, Positrons		Photons	
	Absorption	Scattering	Absorption	Scattering
Atom as a whole	Ionization loss		Photoabsorption < 10 keV	Rayleigh scattering
'Free' shell electron	2 γ Annihilation	Bhabha (e^+e^-) Møller (e^-e^-)	Pair production	Compton effect 1 keV to few MeV
Coulomb field of nucleus	Bremsstrahlung	Coulomb scattering	Pair production > few MeV	Nuclear scattering

Table 2: Classification of electromagnetic interactions; the important processes in LEP are in bold print. The electromagnetic shower is built up due to bremsstrahlung and pair production, since e^+ , e^- and photons have about the same mean-free-path.

particles can escape into the aperture of the vacuum chamber until they are completely absorbed by further interactions.

3 Mechanisms for breakdown processes without radiation

Without radiation an electrical breakdown across the electrode gap in ultra-high vacuum can be triggered by localised field emission or by the impact of charged microparticles. The mechanism governing these processes have been understood for many years and the theory seems to be widely accepted.

This is not the case for the breakdown along the insulator (also called flashover), for which a controversy between several models exists. However, thanks to a new model proposed by C. Le Gressus *et al.* [7, 8, 9] the understanding of the breakdown mechanism across an insulator has made good progress in recent years. In particular, we believe that this model can improve the explanation of radiation triggered breakdown processes. Therefore, the main ingredients of this new model are briefly reviewed.

The charging mechanism in a dielectric can be understood as a polarization and the discharging as a polarization energy relaxation process. A discharge process can be catastrophic (breakdown, failure) if the characteristic dielectric parameters such as permittivity, distribution of defects, and stored energy fulfil certain criteria.

3.1 Charging mechanism due to electrical polarization

1. The carrier localisation occurs in traps formed by polarization charges in the dielectric. The traps are created by inclusions, lattice disorders, and grain boundaries. In the macroscopic description traps are related to the local variation of the dielectric susceptibility χ .

2. Dielectric polarization of an insulator means that a space charge is formed, electrostatic energy is stored, and the free energy increases. The dielectric polarization of an insulator can be produced by any type of **stress** such as mechanical, **electrical**, or **radiation**. Thus the polarization is due to trapped charges and dipole orientation. The trapped charges produce a space charge field, a storage of polarization energy, and a change in the free energy.

3. The polarization energy per trapped charge is about 5χ (eV), so that for Al_2O_3 one obtains 35 eV or 400 000 °K. Most of this energy is concentrated in a small sphere surrounding the trap which contains about 100 atoms. Thus this energy when released would produce a 'thermal peak' of about 4000 °K evaporating all the atoms in the sphere.

3.2 Discharge or dielectric polarization relaxation process

1. The discharge proceeds in two steps: firstly, the charges are de-trapped and then the polarized medium around the de-trapped charge gets depolarized. This de-trapping or de-stabilization of charges can be caused by mechanical shock, **irradiation with photons**, **bombardment with electrons or other charged particles**, or electric field perturbation.
2. After the de-trapping of the charges the polarization energy relaxation occurs, minimizing the free energy in the insulator. The released energy can be transferred to the phonon bath corresponding to the observed light emission prior to catastrophic breakdown and can initiate thermal shock waves.

4 Possible mechanisms for radiation triggered breakdown processes

In an e^+e^- collider environment, where a high number of photons and charged particles (e^+ , e^- , ions, microparticles,...) are present, the fundamental processes mentioned in the preceding chapter become enhanced.

Radiation impinging on the electrodes or ceramic insulators of an electrostatic separator can trigger an electrical breakdown either by the direct impact of synchrotron radiation photons producing photoelectrons or by the incident charged particles. Thus the charged particles, produced in or incident on an insulator, can destabilize the space charge distribution in the dielectric leading to a breakdown.

Radiation triggered breakdown in an insulator has been observed in an experiment [9]. Electrostatic energy was stored with an electron bombardment of 30 kV energy, thus creating a negative space charge because of a secondary emission coefficient $k < 1$. A subsequent bombardment of the charge sample with a lower energy electron beam of 2 keV, implanting positive charges ($k > 1$), then provoked a de-stabilization of the space charge distribution in the insulator leading to a breakdown even in the absence of any external electric field. Thus, we believe that radiation triggered breakdowns across the insulators contribute strongly to the reduced high voltage performance of electrostatic separators in the LEP collider.

We have seen above that both the SR and the electromagnetic interaction of the high energy beam particles can produce high numbers of photons and low energy electrons. The main difference is that the SR is a continuous source, whereas the electromagnetic showers are mainly due to mishaps such as bad beam steering or beam blow-up. The latter can be provoked in order to dump the beams, although it can also arise unexpectedly due to beam instabilities. Thus we might expect that breakdowns due to SR would occur at regular intervals in contrast to breakdowns initiated by electromagnetic showers. This can help to distinguish between the trigger mechanisms.

In the LEP collider we have observed [11] that it is the synchrotron radiation which is at the origin of most of the beam induced or radiation triggered breakdowns in the electrostatic separators. Therefore, we will concentrate mainly on the contribution due to SR.

4.1 Photoelectron yield from synchrotron radiation

The LEP aluminium alloy vacuum chamber was exposed to synchrotron radiation and the photoelectron currents

were measured [12]. The photoyield varied between 0.02 at 1 keV and 0.2 at 10 eV. Thus in the LEP arcs, at 46 GeV, with a SR flux of $\approx 10^{16}$ photons $s^{-1}m^{-1}$ per mA of beam current (photon energy > 10 eV) [10], the rate of photoelectron production is $\approx 10^{15}s^{-1}m^{-1}mA^{-1}$. For the ZX separators placed at the entrance of the LEP arcs photocurrents compatible with these figures have been measured.

4.2 Neutral gas desorption from synchrotron radiation and subsequent ion production

The measurements with the LEP vacuum chamber also showed that the desorption of neutral gas took place, mainly via the intermediate photoelectrons [12]. The gases desorbed were H_2 , CO, CO_2 , and CH_4 . For the dominantly desorbed gas CO a molecular desorption coefficient of $5 \cdot 10^{-2}$ molecules/photoelectron at a photoelectron energy of about 60 eV was evaluated. Thus, the production rate of desorbed molecules is of the order of $10^{13}s^{-1}m^{-1}mA^{-1}$ and the induced pressure increase by about 10^{-8} Pa mA^{-1} for a pumping capacity of $1000 l s^{-1}m^{-1}$.

In LEP the desorbed gas molecules are then ionized by the collisions with the beam particles so that another important source of positively charged particles is created. Breakdown due to ions has not yet been confirmed as an independent mechanism.

4.3 Electromagnetic showers

High energy e^+ and e^- can produce electron-photon showers which result in a large number of low energy electrons. The electrons can trigger directly an electric breakdown in a separator. The electron-photon cascade can also desorb gas molecules from the wall of the vacuum chamber. The gas molecules are then ionized by the circulating beams, so that positive ions are created. Breakdowns due to beam blow-up or missteering have been identified.

5 Breakdowns observed in the LEP vertical separation system operational since 1989

The main parameters of the vertical separation system installed in the the 8 straight sections of LEP are given in Table 3. The high voltage performance, i.e. the spark rate per hour as a function of the mean field strength, is shown in fig. 1. The lower curve summarizes the laboratory tests combined with the beam-off tests measured with a gap of 60 mm. The next curve stems from operation with beam at a gap of 110 mm from August 1989 to August 1991. During this period 8 ZL were

Figure 1: LEP vertical beam separation system: ZL separator spark rate per unit as a function of the mean electric field strength in MV/m.

beam energy	46 GeV
ZL separator length	4.5 m
electrode length	4.0 m
electrode width	260 mm
nominal electrode gap	90 mm
nominal voltage	± 130 kV
nominal field strength	2.9 MV/m
total separation	0.83 mm
conditioning voltage	± 160 kV
conditioning field strength	5.8 MV/m
vacuum pressure	$2 \cdot 10^{-8}$ Pa

Table 3: Parameters of the LEP vertical separation scheme ZL since summer 1991. Before the gap was 110 mm and the field strength 2.5 MV/m. The design field strength was 2.0 MV/m. The ZL separators are bipolar.

operated at 0.6 MV/m without any sparking, 16 ZL at 1.6 MV/m had a spark rate of $(2 \pm 1) \cdot 10^{-4} h^{-1}$, and 8 ZL at 2.5 MV/m a spark rate of $(1.4 \pm 1) \cdot 10^{-3} h^{-1}$. The single point marks a separator with reduced performance due to an air leak which appeared after the bake-out in situ. After a second bake-out the performance of this separator returned to normal.

The upper curve was recorded during a specific measurement in April 1990 aimed at exploring the operational limits of the vertical separators. For this purpose the gap in several separators was reduced to the minimum possible value of 60 mm. Under these circumstances the electrodes were no longer protected against the synchrotron radiation of the quadrupoles by the aperture of the surrounding vacuum chambers and collimators. Due to the high spark rate only measurements at the injection energy of 20 GeV were carried out. It can be seen that at 2.5 MV/m the spark rate is increased by a factor of about 1000 above the standard value for separator operation with beam.

Due to this experience only a modest gap reduction from 110 mm to 90 mm was introduced in August 1991. The corresponding augmentation in the separation field from 2.5 to 2.9 MV/m allowed an increase in the accumulated beam currents in LEP of about 7% [2]. Compared with the design field strength of 2.0 MV/m the gain achieved in the beam current by a larger separation is actually 14%. This shows the importance of a high performance beam separation system and motivates the quest for a better understanding of radiation triggered breakdown, which is still the limiting factor.

In August 1992, we experienced for a period of about

two weeks a striking example of radiation triggered breakdowns in a single unit of the 4 ZL separators installed in point 2. The separators of the even LEP interaction points (IP) are only used during the accumulation and acceleration processes and thereafter switched off to bring the beams into collision. Nevertheless, always in the same single unit, typically three breakdowns were regularly recorded during this short period (lasting about one hour) which corresponds to an increase in the spark rate by more than two orders of magnitude as compared with normal beam operation. Furthermore, the sparks were only recorded for the positive polarity (bottom electrode), whereas the negative electrode stayed at its nominal voltage, so that any breakdown across the gap could be excluded. The high background in the experiment and the strange separator sparking disappeared when the faulty monitor which had resulted in a bad beam steering, was repaired.

In LEP the beams are currently dumped by dephasing the voltages of the accelerating cavities, so that the beam orbits spiral inwards and the particles are gradually absorbed on aperture limiting collimators. This process often provokes breakdowns in the separators located next to the collimators.

We have also observed coincident breakdowns in two separators within a time resolution of less than 1 ms, although these units are 40 m apart and operated at very different field strengths of 2.9 and 0.6 MV/m, respectively, with independent high voltage circuits. These events were always correlated with bad beam steering and high background problems.

We believe that all these breakdowns resulted from electromagnetic showers produced by the mis-steered beams interacting with the LEP vacuum chamber. SR could not explain these effect, because the ZL separators are installed in the straight sections of LEP, where they are protected by collimators from the strong dipole SR and, due to the large electrode gap, the quadrupole SR should not play a major role.

6 Breakdowns observed with the recent LEP pretzel separation system

The electrostatic separators ZX for the pretzel separation scheme of LEP are non-symmetric or unipolar i.e. one electrode is connected to high voltage and the opposite electrode is connected to ground. Originally they were designed for operation in the SPS proton antiproton collider with negative polarity only. During 1991 half of the necessary 8 ZX units were installed; this allowed a series of feasibility studies with the so-called 'Half Pretzel Scheme' (fig. 2) [5, 11]. In particular,

Figure 2: ZX 'half' pretzel scheme for studies in 1991

when operating the separators with the negative design polarity, an unacceptably high spark rate in the presence of beam was observed. It was found empirically that the spark rate problem was almost cured by operating the separators at positive polarity. This year all eight separators are in place (fig. 3) and, furthermore, a test area TAZ - consisting of a ninth ZX unit together with horizontal collimators, charged particle traps and improved spark diagnostics - has been added at the left of IP 4 in order to study the mechanism leading to beam induced breakdown [11].

beam energy	46 GeV
ZX separator length	3.38 m
electrode length	3.0 m
nominal electrode gap	120 mm
nominal voltage	180 kV
nominal field strength	1.5 MV/m
beam size at mid-arc	$\sigma_x = 2.66$ mm
total separation	16.9 mm = $6.37 \sigma_x$
conditioning voltage	275 kV
conditioning field strength	5.8 MV/m
vacuum pressure	$2 \cdot 10^{-8}$ Pa

Table 4: Parameters of LEP horizontal pretzel separation scheme for the feasibility studies in 1991. The ZX separators are unipolar. The LEP experiments are installed in the even interaction points (IP).

Figure 3: ZX full pretzel scheme 1992 including TAZ

6.1 Summary of the measurements from 1991 with the 'Half Pretzel Scheme'

The main parameters for the Pretzel separation scheme for 1991 are given in Table 4.

Without beam the spark rate of the separators is negligible, i.e. $< 10^{-4}$ per hour. This result has been obtained by measuring the spark rates for negative and positive polarities at higher fields and then extrapolating them to the nominal field. With beam the spark rates behave as follows: For the negative polarity they increase dramatically, whereas for the positive polarity it seems that they still remain acceptable. For the negative polarity there is a clear correlation between the increase in the spark rate and the presence of Synchrotron Radiation (SR) depending on its origin. The Synchrotron Radiation has two sources which might affect the separators: (i) The most important source is from main bend dipoles of the LEP arcs; the total flux incident on the outer electrode of a Pretzel separators is as high as $2 \cdot 10^{16} \text{ photons s}^{-1}$ per mA of beam current, with photon energies $\geq 10 \text{ eV}$. The flux of scattered SR photons arriving at the inner electrode is lower by about a factor of 1000. The critical energy is 69.7 keV. (ii) The other source is from the quadrupoles of the long straight sections of LEP; this flux is much lower, but the critical energy is more difficult to estimate; it could be higher depending on the e^+ and e^- trajectories in the quadrupoles.

For the dipole SR and for the **negative** polarity a strong increase in the spark rate at nominal field by about a factor of about 10^4 has been found. For the quadrupole SR the increase is much smaller and esti-

Figure 5: ZX separator in IP2: HT dark current dependence on the position of the outer jaw (curve a) of the horizontal collimator. Curves b,c are for the position of the inner jaw. Curve d: no beam. Configuration as for fig. 4a

mated at $< 10^3$. The important difference in the spark rates induced by Synchrotron Radiation from the dipoles and from the quadrupoles rules out the possibility that 'higher order mode losses' might be the origin of the beam induced sparking.

Measurements with negative polarity:

A detailed study, carried out at 46 GeV and for negative polarity, on the correlation between the spark rate and Synchrotron Radiation from dipoles has shown (fig. 4):

1. For a fixed field the spark rate is rather independent of the electrode gap.
2. The spark rate is about the same when the direct photons hit the high tension HT electrode or the grounded electrode (fig. 4 a or b).
3. The spark rate per ZX at the nominal field strength of 1.5 MV/m is $(3.6 \pm 0.6) \text{ h}^{-1} \text{ mA}^{-1}$.
4. The direct high energy photon flux incident on the separator electrodes is not the main source producing the sparks. This has been verified, for fig. 4a, by a scan with a horizontal collimator (fig. 5). The photocurrent produced by Synchrotron Radiation photons, hitting the HT electrode, is reduced by factor 15 when the collimator is closed to protect the both the HT and the grounded electrodes. The spark rate, however, is only reduced by a factor of 1.5 ± 0.5 . Therefore, low energy photons and electrons produced by the photo effect appear to play an important role in the separator sparking mechanism.

SPARK RATES IN PRETZEL SEPARATORS FOR SYNCHROTRON RADIATION FROM ARC DIPOLES FOR e+, e- at 46 GeV.

beam	e +	e -	e +	e -	e +	e -	e +	e -
ZX in point	2	4 8	2 6		2	4 8	6	
Spark rate τ	high	high	high		negligible	negligible	negligible	
at 1.5 MV/m (1/h/mA)	~ 7	~ 7	~ 7		< 0.02	< 0.1	< 0.1	
Smaller τ with large gap	no	yes	no					
Smaller τ for closed collimator	no							

direct photon fluxes on exterior electrode F_{direct}
 scattered photon fluxes on int/ext electrode

: $\sim 2.10 \text{ E}+15 \text{ 1/s/mA}$
 : $\sim F_{\text{direct}} \cdot 10 \text{ E}-3$

Figure 4: ZX spark rate dependence on polarity in 1991. The total direct SR photon flux on the exterior electrode is $2 \cdot 10^{15} \text{ s}^{-1} \text{ mA}^{-1}$ for energies $\geq 1 \text{ keV}$. For lower cut-off at 10 eV, the flux increases by a factor 10. The scattered flux is lower by a factor of 1000.

Measurements with positive polarity:

A study for positive separator polarity at 46 GeV gave the following results:

1. With an open collimator no sparks were observed in the same separator after commuting from negative to positive polarity (fig. 4c) during a period of 2 hours at a field strength of 2.5 MV/m and during one hour at 3.0 MV/m.
2. Under these conditions the spark rate with negative polarity would have been $(67 \pm 8) \text{ h}^{-1} \text{ mA}^{-1}$.
3. The SR induced dark current measured with positive polarity and open collimator was only $4 \mu\text{A}$. This value is low compared with $32 \mu\text{A}$ measured under the same beam conditions with negative po-

larity. The large difference in the dark currents results from the fact that for positive polarity the HT electrode can only collect photoelectrons produced almost exclusively by scattered SR photons.

4. For a closed horizontal collimator the photocurrent produced by the scattered SR photons and accumulated by the positive electrode is only reduced to $2 \mu\text{A}$; thus a collimator is less efficient in reducing the flux of scattered SR photons.

Conclusions:

- The ZX separators must be operated at positive polarity.
- For a full Pretzel scheme with a single beam current of 4 mA (0.5 mA per bunch) and the separators

Figure 6: Total TAZ separators dark current (μA) dependence on total e^+ beam current for two gaps

operated at 1.5 MV/m, this would then correspond to a period between two sparks of > 1.4 hours.

- An operation of the full Pretzel scheme with the original negative polarity would be completely impossible, since for the same beam current the period between two sparks would be as short as 2 minutes.

6.2 Measurements with the full pretzel scheme in 1992

Only a few measurements have been possible to date. The first results obtained with the new test facility TAZ are as follows [13, 14]:

1. For most of the breakdowns the detectors on both the high tension and on the grounded electrodes indicate a voltage drop, so that breakdowns do not occur only as flashovers across the insulator. However, the calibration of the spark detectors still has to be checked.
2. The dark current measured at the high tension electrode produced by dipole SR is proportional to the total beam current (fig. 6).
3. The charged particle traps: Up to the maximum voltage of ± 7 kV there was no effect on the dark current in either separator. So we conclude that the dark current is produced inside the separator and ions travelling along the vacuum chamber should not be the cause of beam-induced breakdowns.

During two 24 hours measurement sessions in July and August of this year LEP has been successfully operated for the first time with $8 e^+ 8 e^-$ bunches, from accumulation to acceleration and beams in collision. Only one of the 8 ZX separators had breakdowns which, however, did not cause either any beam loss nor 'background spikes' for the experiments. This was the separator installed in the TAZ zone. The high spark rate in this

particular separator might be due to its specific construction (the grounded electrode is insulated to enable separate measurement of the dark current and to identify sparks across the electrode gap). 80 % of the sparks recorded were due to breakdowns across the gap. The spark rate in the TAZ separator was $.6 \pm .2 h^{-1}$ at a field strength of 1 MV/m for an operation at 46 GeV with a total beam current of about 2 mA. The other seven separators did not have a single breakdown during all measurements with similar currents; at 46 GeV this corresponds, for the seven units, to a period between two sparks of > 27 hours at a field strengths varied between 1 and 1.3 MV/m.

More data will be obtained soon from the test facility TAZ and from Pretzel runs preparing the transition to physics operation foreseen in October of this year.

7 Breakdowns observed in some other e^+e^- accelerators and colliders

7.1 CESR

CESR at Cornell University, Ithaca, USA is an e^+e^- collider operating at 5.3 GeV. With the help of the horizontal pretzel separation system, exploited there for the first time, the number of bunches could be raised to 7 per beam. The separation system comprises 4 horizontal separators of 2.54 m electrode length and a gap of 121 mm operated at 1.65 MV/m. The separators are bipolar.

Figure 7: CESR: Spark rate per separator as a function of the total beam current.

Beam currents are limited by vacuum chamber heating due to higher order mode losses and radio frequency and separator sparking to 11-14 mA/bunch depending on the condition of the equipment [15]. The breakdown rate per separator is less than one per day up to a total current of 130 mA, and increases for higher currents, like the flux of synchrotron radiation (fig. 7) [17]. It was also found that the separators show the polarity effect, discovered with the ZX separators of LEP.

7.2 TRISTAN

TRISTAN at KEK, Tsukuba, Japan, is an e^+e^- collider operating at 29 GeV. With two bunches per beam the total current is 14.5 mA. At TRISTAN, due to a special optics, the separators are not regularly used. Radiation triggered breakdown problems arose with the increase in beam energy; then the reliability of the superconducting cavities decreased. An improvement of the trip rate of the cavities close to the arcs was achieved, after a mask absorbing the synchrotron radiation was installed. It was found that the alignment of this mask had to be rather accurate and it reduced the number of photoelectrons produced in the cavity. Both observations support the hypothesis that the SR is at the origin of the breakdowns.

7.3 SPS

The SPS at CERN serves as the last pre-accelerator in the LEP chain, increasing the lepton energy from 3.5 to 20 GeV. During the first acceleration test with e^+ it was found that above 6 GeV the electrostatic septa, needed for the extraction of protons, started to spark at a very high rate. Such a behaviour was not entirely unexpected taking into account the high flux of synchrotron radiation photons. Interesting features were observed such as prompt and delayed sparks. Finally, the problem was cured by installing movable shutters intercepting the synchrotron radiation flux during the positron acceleration cycle [19].

8 Conclusion

Radiation triggered breakdown phenomena are an important limitation in the performance of DC and AC equipment such as electrostatic separators or superconducting cavities, generally installed in an e^+e^- collider. A better understanding of the mechanism of beam induced breakdowns would allow an improved construction, so that better performances could be achieved at lower cost. Furthermore, an increased reliability would be a considerable asset for the operation of such a complex device as a high energy e^+e^- collider.

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