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**PSEUDO-SPARK SWITCH DEVELOPMENT FOR THE
LHC BEAM DUMPING SYSTEM**

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Abstract

The kicker magnet pulse generators for the beam dumping system of CERN's Large Hadron Collider (LHC) require fast high power switches (35 kV, 30 kA, 8 μ s) of very low repetition rate (only a few pulses per day). Cold cathode tubes like pseudo-spark switches look suitable for this kind of application, as they do not suffer from cathode-heater lifetime limitations and may guarantee a quasi unlimited operation time. Pseudo-spark assemblies are therefore under development with the aim of obtaining a switch tailored to two main requirements of the LHC dumping system, a very low prefire rate ($\sim 10^{-4}$) and a large ratio of maximum to minimum operation voltage (~ 15). It is intended to achieve these goals with a 2-gap or 3-gap version employing a ferroelectric trigger in each of the gaps.

Experimental results on several 1-gap prototypes of different electrode diameter will be reported. Two of the prototypes have been mounted in a sealed-off version, equipped with a deuterium gas reservoir. The erosion behaviour has been investigated for different electrode materials, pure tungsten, thoriated tungsten and tungsten/rhenium (5% Re). Important differences in the quenching behaviour between pure and thoriated tungsten have been found. The incorporation of these results into a 2-gap beam dump switch, soon to be assembled, will be discussed.

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Abstract

The kicker magnet pulse generators for the beam dumping system of CERN's Large Hadron Collider (LHC) require fast high power switches (35 kV, 30 kA, 8 μ s) of very low repetition rate (only a few pulses per day). Cold cathode tubes like pseudo-spark switches look suitable for this kind of application, as they do not suffer from cathode-heater lifetime limitations and may guarantee a quasi unlimited operation time. Pseudo-spark assemblies are therefore under development with the aim of obtaining a switch tailored to two main requirements of the LHC dumping system, a very low prefire rate ($\sim 10^{-4}$) and a large ratio of maximum to minimum operation voltage (~ 15). It is intended to achieve these goals with a 2-gap or 3-gap version employing a ferroelectric trigger in each of the gaps.

Experimental results on several 1-gap prototypes of different electrode diameter will be reported. Two of the prototypes have been mounted in a sealed-off version, equipped with a deuterium gas reservoir. The erosion behaviour has been investigated for different electrode materials, pure tungsten, thoriated tungsten and tungsten/rhenium (5% Re). Important differences in the quenching behaviour between pure and thoriated tungsten have been found. The incorporation of these results into a 2-gap beam dump switch, soon to be assembled, will be discussed.

Introduction

CERN, the European Particle Physics Laboratory, plans to build an accelerator to bring protons and ions into head-on collision at higher energy than ever achieved before. This Large Hadron Collider (LHC), a 7 TeV superconducting machine, will be housed in the existing LEP tunnel of 27 km circumference. Two beams of 2.8×10^{14} protons each will circulate in opposite directions and collide at a centre of mass energy of 14 TeV. The total stored beam energy of up to 0.66 GJ has to be disposed of

reliably at the end of a physics run and also in case of equipment failures. A beam dumping system must therefore be available that extracts at any time and at all beam energies from 0.45 to 7 TeV both beams from the collider orbits and directs them in a controlled way onto external absorbers.

The dumping system employs fast kicker magnets that extract the beams in one revolution. They are excited by pulses of 3 μ s rise time and about 90 μ s flat top duration. In total 2×12 magnets are needed, each powered by its own pulse generator.

The pulser

For the electrical circuit of the pulse generator a capacitor discharge has been chosen, in combination with a free-wheel diode stack in parallel to the magnet. This circuit produces a pulse of 3 μ s rise time and about 2 ms fall time, of which only about 90 μ s will be used. The droop of about 5% during these 90 μ s is compensated by a low voltage, high current capacitor discharge in order to produce a flat top for extraction. Compared to standard LC pulse forming networks this circuit is simpler, less costly and, in particular, requires conduction of the main switch only during the first 8 μ s of the pulse. The charging voltage of the pulser needs to be proportional to the beam momentum over a wide dynamic range, from injection at 0.45 TeV/c, corresponding to 2.25 kV, to top momentum of 7 TeV/c, corresponding to 35 kV. During a collider run of e.g. 20 h the pulsers are continuously under voltage. They are triggered at the end of the run (or in emergency situations) to dump the beams. A more detailed description of the pulser is given in Ref. [1] and [2].

Switch requirements

Between controlled abort operations the beam dumping system must stay absolutely reliably in the ready-to-abort state without any prefire switching.

The main part of the reliability and safety functions has to be carried by the 24 high power switches of the pulse generators. In case of an accidental untriggered discharge of one of the switches the beam would be deflected into the collider vacuum tube and cause severe damage to machine components. Therefore, in this event the other 11 generators are triggered within 300 ns to deflect the beam into the extraction channel. To achieve a disturbance free collider operation with this large number of switches the rate of untriggered discharges of a single tube must be kept very low. The basic switch requirements are listed in Table 1.

Table 1

voltage range	2-35	kV
peak current	+30/-15	kA
current conduction time	8	μ s
charge transfer per pulse	0.11	C
repetition time	minimum	30 s
	typical	5-20 h
lifetime	10^5	pulses
max. jitter	30	ns
prefire rate	$< 10^{-4}$	

We consider for this application 3 different types of switches which are actually under study: thyratrons, modified gate turn-off thyristors (GTO's) and pseudo spark switches (PSS's). The final choice will be made when the development and thorough life testing of the 2 latter types has been terminated. Globally these switches can be characterised as follows.

Thyratrons require due to the limited lifetime of the heated cathode a costly replacement every 3 to 4 years, whereas their large switching capabilities are only poorly exploited in such a low repetition rate application. Furthermore, a sufficiently low prefire rate can probably only be obtained with a costly 3-gap version which has for this application a too low voltage operation range and would complicate considerably the tracking of the system voltage with the beam energy. Apart from these drawbacks thyratrons are suited for this type of application and an EEV 2-gap version (type CX 1575C) is actually mounted in a prototype generator and functions well.

Modified GTO's are novel, very promising fast power switches. Until recently, the low di/dt capabilities of power semiconductors precluded their use in fast kicker magnet pulse generators. In 1992 however, tests performed within our team at CERN have shown that a current rate of rise of $20 \text{ kA}/\mu\text{s}$ is achievable with a modified GTO structure. This has encouraged us to pursue the development of a fast,

35 kV GTO switch. Preliminary results are also presented at this symposium [2].

Pseudo spark switches have several advantages compared to thyratrons for low repetition rate applications. This had already been recognised in the early design stages of the LHC beam dumping project and a program was started in 1990 to develop a PSS tailored to the requirements of this system. The main PSS advantages are :

- an operation voltage range large enough to cover the dynamic range of the LHC from injection to top energy,
- a quasi unlimited lifetime for the low repetition rate required,
- a possibly negligible prefire rate.

After a short description of the achievements of our development work on pseudo spark switches during the last years we will present recent test results and discuss the implementation of the switch into the dumping system..

Pseudo spark switch development program

Up to now six 1-gap and 2-gap prototypes (PSS1-PSS6) of increasing performances have been constructed and tested to approach the switch requirements summarised in Table 1. PSS7, soon to be assembled, will be a semi final version of the beam dump switch, composed of 2 PSS6 gaps in series with one common gas reservoir. It shall in principle fulfil all requirements of Table 1. The final number of gaps will depend on the results of PSS7. Fig. 1 shows a schematic cut through PSS6.

Fig. 1 Schematic section through PSS6

The main achievements obtained so far are listed below.

Ferroelectric trigger. Field-excited electron emission from ferroelectrics, discovered at CERN in 1988 [3], was already used in 1990 in our first prototype as a powerful trigger source and has since then been the most reliable, steadily improved single component of the pseudospark switch [4]. The ferroelectric trigger provides a large operation voltage range (~100 V - 35 kV), important for covering the whole energy range of the LHC from injection to top energy.

Tungsten electrodes. After testing of stainless steel, graphite and Mo, we had originally retained as most suitable materials W and the compound materials W/ThO₂ and W/Re. More recent tests, described below, have however led to the elimination of the compound materials. The preferred electrode material is therefore pure W.

Ring gap electrode geometry. The standard PSS geometry consisting of 2 axially aligned cylindrical holes of about 3 mm diameter has been abandoned in favour of a geometry with 2 axially aligned ring gaps of 14.5 mm (PSS's 4/5) and 18.3 mm (PSS6) mean ring gap diameter (Fig. 1). The ring gap with a width of 2.7 mm has been introduced in 1992 to reduce current density [4]. This has resulted in a marked decrease of erosion. Inspection of the electrode surface after life tests has furthermore shown that the discharge covers perfectly homogeneous the whole ring gap. These results suggest, together with the comparably high on-state resistance of about 30 mΩ at 40 kA that the switch does not operate in a constricted vapour arc mode of high energy density, but rather in a diffuse superdense glow mode of relatively low energy density and little electrode erosion. (Alternative geometries to reduce the current density, like parallel operation of several separated axially or radially oriented discharge holes [5] have shown a less homogeneous current distribution and the tendency to arc-discharges.)

Long path to the "triple point". To better protect the "triple point" zone anode-cathode-insulator from gaseous erosion products the path length of the protection chicane in the electrode supports has been increased from 50 mm to 150 mm (Fig. 1).

Insert electrodes. For cost reasons anode and cathode have been separated into 3 parts: a large stainless steel support which provides the chicane and can be recuperated after a life test, a small stainless steel electrode holder, to be screwed into the support and the proper W electrode insert which is brazed onto the electrode holder.

Main insulator diameter. The diameter of the main insulator has been increased from 75 mm to 103 mm (inside) in order to decrease the curvature in the chicane and to accommodate the increased diameter of the electrode ring gap.

D₂ gas reservoir. To allow an external gas pressure control the originally favoured He has been replaced by deuterium. This has allowed to equip the tubes with a zirconium getter that acts as D₂ gas reservoir. The getter binds most spurious gas contaminations and may contribute to the improved performances.

350°C bake out facility. A 350°C bake out facility has been constructed where all tubes are heated in situ before being filled with gas.

Two-gap version. A 2-gap version has been tested successfully to study triggering synchronisation and to confirm doubling of voltage holding [6].

Brazed metal-ceramic technology and metallic gaskets. Contrary to the usual practice employed for switches in metal/ceramic technology the PSS remains demountable after life tests and most of the elements can be recuperated. This is achieved by equipping the main insulator with brazed-on stainless steel flanges. The active inner switch components are then mounted on stainless steel disks that are clamped to the insulator flanges via metal gaskets. The whole assembly is bakeable at 350°C.

Discussion of recent test results

In the last year two prototypes, PSS's 4 and 5, have been tested. Recently we have started the testing of PSS6. The main aim of these tests was the selection of the most suitable electrode material, the investigation of the causes for quenching and a more detailed analysis of the causes for pre-firing.

All three switch versions have ring gap electrodes with a mean ring hole diameter of 14.5 mm for PSS's 4 and 5 and 18.3 mm for PSS6. PSS4 is a clamped version with external gas supply, PSS's 5 and 6 are sealed-off types with incorporated gas reservoir. Electrode material in PSS4 was either W (PSS4b) or W for the outer ring and W/Re (5% Re) (PSS4a). PSS5 was equipped with thoriated W and PSS6 with pure W electrodes. PSS4 did not undergo an in situ bake out whereas PSS's 5 and 6 were heated to 350°C during 10 hours.

The life tests are performed in a capacitor discharge circuit that produces a damped current oscillation of up to 47 kA for 22 kV charging voltage. The pulse shape is shown in Fig. 2. PSS4a has been tested for 2.2×10^4 shots, PSS4b for 3.7×10^4 shots

and PSS5 for 10^5 shots. PSS6 has up to now made about 5×10^4 shots. The following main test results were obtained.

Fig.2 Pulse shape of test current

Quenching behaviour.

PSS's 4 and 5 differed markedly in the quenching behaviour, a very fast current interruption in the course of the discharge. In PSS4 quenching did not occur at the normal working pressure (30 to 50 Pa). At lower gas pressures it appeared in a narrow voltage range (2.3-2.6 kV at 28 Pa, 1.3-3.2 kV at 12 Pa). In PSS5 however, quenching occurred already at 40 Pa in the voltage range 1.4-8.75 kV. At a pressure of 60 Pa the range decreased slightly (1.75-7.35 kV). After exposing the switch to atmospheric pressure, quenching disappeared for about 700 shots and reappeared thereafter as before. In PSS6 quenching was absent for about the first 1000 pulses and then appeared intermittently.

These results confirm earlier measurements where quenching was mainly observed with thoriated but not with pure W electrodes. We have therefore discarded thoriated tungsten. The quenching phenomenon is however not yet fully understood and further investigations are required.

Erosion

The electrodes of PSS4 were homogeneously eroded, without visible spark spots, indicating that the pseudo spark covers uniformly the entire circumference of the ring gap. The whole surface of the central disk, exempt the border on the ring gap, has a very smooth aspect which lets us suppose that

the surface is melting entirely during the discharge. The material has uniformly been eroded off, with more material taken away near the ring gap than in the centre (Fig. 3). The outer ring electrode, to the contrary, is eroded only over a radial width of about 2.5 mm, showing a very precise erosion border line and indicating that the temperature falls off rapidly in outward direction.

Fig. 3 Schematic section through the electrodes showing erosion zones (black) with plane of needles

A characteristic erosion pattern are small, very brittle W needles growing in radial direction from the central disk and the outer ring electrodes into the ring gap. They are located at the border of the melting zone in a plane perpendicular to the tube axis, that roughly coincides with an electrical potential plane during voltage hold off. The needles have a mean length of about 0.7 mm and a density of about 1 needle/mm (Fig. 4). Due to this orientation of the needles, and possibly also due to the formation of a predischage plasma zone around the needles, the withstand voltage is not appreciably reduced. The needles may however contribute to prefiring, as discussed below.

Fig. 4 Erosion Pattern with needles

If during repetitive pulsing the needles grow, their tips are probably molten-off by the discharge and fall into the hollow anode or onto the grid electrode in the hollow cathode, provided the tube is mounted vertically. In these places the erosion products do not do much harm. A horizontal mounting of the tubes is however probably precluded. Eroded particles would then be deposited in the main anode/cathode gap causing probably a strong reduction in withstand voltage. The eroded material has to a large extent the shape of perfect spheres with a diameter of several tenths of a millimetre, probably formed during very rapid solidification.

The large needle size has led us to discard the costly and difficult to machine W/Re alloy as electrode material whose reported fine grain size can not be exploited in the presence of the large erosion needles.

Erosion in PSS5 was less uniform and concentrated on one spot, most likely due to an unidentified stress point. This behaviour is however not considered as characteristic.

Prefiring

With PSS's 4 and 5 the rate of untriggered discharges was about 1% and the repetition time could not be lowered to less than 17 s in order not to provoke spurious prefiring. At 20 kV DC the prefire rate was about once per 3 to 5 hours.

With PSS6 an improvement of the prefire rate of more than 2 orders of magnitude has been observed. In the pulsed mode 2 prefire discharges were observed during a life test of 5×10^4 pulses at a repetition time decreased to 10 s and a voltage increased to 22 kV. During overnight and weekend DC tests a voltage of 27 kV could be held over repeated periods of 15 h and 65 h respectively for a total time of more than 500 h without any prefiring. The improved performances are attributed on the one hand to the improved general mounting conditions (high temperature bake out of all materials prior to assembly, clean room assembly, improved in situ bake out of switch and gas feeder lines, liquid nitrogen trap for gas filling, addition of a sputter ion pump that lowered the pressure after bake out to less than 10^{-9} Torr). Also the increased diameter of the central electrode disk contributes probably to the improved pulsed mode performance at higher repetition rate. A new conditioning method certainly helped to obtain the excellent DC voltage holding. Conditioning is now done by triggering the switch with 1 pps repetition rate from a 5 nF capacitor whose voltage is gradually increased up to 35 kV.

A more detailed study of the prefire discharges reveals that the phenomenon has at least 2 different sources. It is either caused by operating too close to the Paschen curve, the natural breakdown level of a gaseous switch, or by electrode damage during the high power spark, when the severe thermal and mechanical shocks create points of high electrical field stress and electron emission. The former cause leads mainly to discharges on the large chicane areas and the "triple point" zone. This fact can be clearly observed during the first conditioning of a switch, when nearly all prefire flashes can be seen through the semi transparent alumina insulator. This cause can be eliminated by using several gaps in series thus working far below the Paschen border.

The latter cause can be eliminated by frequent reconditioning of the switch during the pulse test. In this case prefiring should occur on the electrode ring gap near the axis. This assumption is supported by the observation that prefire flashes can only rarely be seen through the insulator when conditioning during a pulse test because most of the discharges are hidden behind the long metallic chicanes.

Outlook

A further analysis of the operation mode of the LHC and the reliability requirements of the beam dumping system have shown that repeated PSS conditioning would be useful and is compatible with LHC operation. In fact, before each filling of the LHC with protons a checklist-type program must be scheduled that controls the correct functioning of all vital elements of the beam dumping system. Of prime importance is here the voltage holding of the 24 power switches. It is therefore intended to check before each fill the withstand voltage by means of an automatic test and conditioning program. Ample time is available for these tests, when the current of the superconducting magnets is slowly lowered after the physics run to its injection level. The conditioning program foreseen will pulse each gap of the PSS separately at high repetition rate and low current from a power supply whose voltage is increased within about 100 s up to 35 kV. The power is fed to the PSS gaps by means of a set of computer controlled high voltage relays. This method has also the important additional advantage of being able to determine precisely after years of operation the reliability state of a switch.

Originally it was considered necessary to equip PSS7 with 3 gaps in order to fulfil the stringent reliability requirements concerning prefiring. The important performance increase of PSS6 has now led

us to believe that a 2-gap version may be sufficient. The maximum voltage per gap is then 17.5 kV whereas the long term withstand voltage measured in our experiments is 27 kV. The resulting safety factor of more than 50% is considered sufficient to guaranty a trouble free operation of the 24 switches of the LHC beam dumping system.

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References

- [1] G.H. Schröder and E.B. Vossenberg, "A Prototype High-Power Pulse Generator for the Beam Abort System of CERN's Proposed 16 TeV Collider LHC" in Proc. 19th Pulse Power Modulator Symp., San Diego 1990, p.104.
- [2] J. Bonthond, L. Ducimetière, M. Evans, E.B. Vossenberg, F. Wakeman, R. Youdan, "High Current, High di/dt Switching with Optimised GTO Thyristors", this symposium
- [3] H. Gundel, H. Handerek, H. Riege and E.J.N. Wilson, "Copious electron emission from PLZT ceramics with a High Zirconium Concentration", *Ferroelectrics*, vol. 100, p.1, 1989.
- [4] L. Courtois, P. Faure, H. Handerek, H. Riege and G.H. Schröder, "Development of High Power Switches for the LHC Beam Dumping Pulser" in Proc. Third European Particle Accelerator Conf. , Berlin, 1992. Ed. Frontiers, 1992, p. 1597.
- [5] T. Mehr, J. Christiansen, K. Frank, A. Görtler, M. Stetter and R. Tkotz, "Investigations about Triggering of Coaxial Multi-channel Pseudospark Switches" in *IEEE Trans. on Plasma Science*, Vol. 22 No 1, Febr.1994, p. 78.
- [6] P. Benin, L. Courtois, P. Faure, H. Handerek, H. Riege, K. Schmidt and G.H. Schröder, "High Power Gas Switches Triggered by Ferroelectrically Generated Electron Beams" in Proc. of the 9th Int. Pulsed Power Conf., Albuquerque 1993.