# Development of High Power Switches for the LHC Beam Dumping Pulser

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*Abstract*

The power switches for the pulse generators of the beam dumping system of the Large Hadron Collider (LHC) have to commute 35 kV / 30 kA with very high reliability. Prototype hollow-electrode switches have been designed, constructed and tested. The one-gap tubes are filled with low-pressure (30 Pa) helium. The LHC application requires less than $10^5$ pulses per year and the intention is to use sealed switches, possibly without gas reservoir. The effects of electrode erosion and current quenching have been studied. With a new type of trigger based on a pulsed electron beam emitted from a ferroelectric disk, the switch was triggered between 150 V and 35 kV. The trigger system has operated for several $10^5$ shots with high reliability, switching pulse energies of several kilojoules. The various test results are reported and future improvements are suggested.

## 1. INTRODUCTION

The maximum energy stored in each of the two LHC beams amounts to 583 MJ. The loss of only a small fraction of the beam will induce quenches in the superconducting magnets and larger losses would cause damage or destruction of machine components. A beam dumping system is therefore required which removes the beams safely from the collider at the end of a physics run and in emergency situations. It will also be used during setting-up and machine studies [1].

The beam dumping system uses fast kicker magnets to extract the protons in one revolution from the collider and dispose them on external absorbers. The kickers are powered by pulses of 3 µs rise time and a flat-top duration of about 90 µs, corresponding to one beam revolution. To avoid deflection during the rise time, each beam contains a gap slightly larger than the rise time which is synchronized with the start of the deflection. A total kick strength of 2x18 Tm is needed to extract the beams at top energy. Because of space restrictions in the collider, the magnets must operate at a relatively high field of about 0.8 T and are powered by high current pulses of up to 30 kA. To obtain the short rise time, 2 x 22 magnets of 1 m length are required, each powered by its own pulse generator. During a collider run of up to 20 h the generators are continuously under high voltage. They are pulsed at the end of the run to dump the beams.

After a description of the pulsers and the requirements on their power switches this paper presents development work on hollow electrode switches, novel low-pressure gas tubes particularly well suited for this application.

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## 2. THE PULSER

The pulser is composed of an energy storage capacitor connected via a bi-directional switch to the magnet which is bypassed by a stack of inverse diodes. The capacitor is continuously charged proportional to the beam momentum up to a maximum voltage of 35 kV. When closing the switch the current rises within 3 µs to 30 kA. At maximum current the magnet voltage reverses and the diodes short-circuit the magnet. The switch current falls within about 2 µs to -15 kA (Fig. 1) and decays then in 6 µs, whereas the magnet current decreases slowly with a time constant of about 300 µs due to the freewheel diode loop. To produce a droop-free flat top for dumping the decay is compensated during 90 µs.

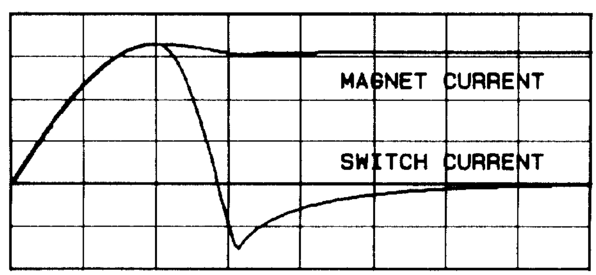


Fig. 1 Switch and magnet currents (10 kA/div., 2 µs/div.)

## 3. SWITCH REQUIREMENTS

In case of an accidental untriggered discharge of one of the power switches the beam would be deflected into the vacuum tube and cause damage to machine components. Therefore in this event all 22 generators are triggered within 300 ns to deflect the beam correctly into the extraction channel. The deflection is however not synchronized with the beam gap and therefore a small portion of the beam will be incorrectly deflected during the rise time and lost in machine equipment. The protection against these losses is actually under study. To achieve with this large number of switches under high voltage a disturbance free collider operation the number of untriggered discharges of a single tube must be kept at a very low rate.

The basic switch requirements are listed in Table 1.

Table 1

| | |
|---|---|
| voltage range | 1.5 kV - 35 kV |
| max. current amplitude | +30 kA / -15 kA |
| pulse duration | 12 µs |
| charge transfer per pulse | 150 mC |
| repetition time minimum | 10 s |
| typical | 5 h - 20 h |
| number of pulses | $10^5$ |
| max. jitter | 30 ns |
| nb. of untriggered discharges | < 1 in 25 years |

For this application the standard power gas switches, thyratrons and spark gaps, have several disadvantages.

Due to their lifetime limited heated cathode thyratrons require costly replacement every 2 to 3 years. On the other hand the large switching capabilities are only poorly exploited seen the low repetition rate of about once per several hours. Furthermore, a sufficiently low rate of untriggered discharges can probably only be obtained with at least 3-gap versions raising the minimum operation voltage and the cost.

High pressure spark gaps are also not very well suited because of their small operation voltage range of about 2 to 3, whereas a factor of about 20 is desirable. Also, the high energy density of the constricted high pressure spark causes strong electrode erosion, incompatible with high reliability.

Novel low pressure hollow-electrode-type switches equipped with recently developed ferroelectric triggers avoid the disadvantages of the standard gas tubes. They have a large operation voltage range of about 100, allowing to work far below the self breakdown voltage thus increasing the safety against untriggered discharges. The hollow electrode switch promises therefore in addition to a quasi unlimited lifetime a high reliability. A program has been launched to develop these switches for the beam dumping system.

## 4. THE HOLLOW ELECTRODE SWITCH

### *4.1 Principle [3]*

Two hollow cylindrical electrodes, forming anode and cathode, are placed on the same axis at a distance of some mm (Fig. 2). Both electrodes have a small axially centered hole. The assembly is sealed off by a cylindrical insulator and operates under low pressure deuterium or helium. A trigger located in the hollow cathode space initiates a diffuse glow-type discharge that extends in very short time through the hole into the main gap where the plasma is confined in a small volume around the axis. The discharge is sustained by surface emission from the surrounding of the cathode hole which is heated to high temperature by the discharge.

The hollow electrode geometry has several advantages compared to the geometry of thyratrons: The control grids are located outside of the main discharge and are therefore less strongly damaged. Also, the radial extension of the discharge is limited to the region around the axis holes. The walls can then efficiently be protected by screens and remain clean.

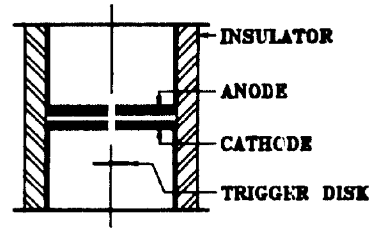


Fig. 2 Principle of the hollow electrode switch

### *4.2 Basic Design*

The tube is built in all metal / ceramic UHV technology. Both electrodes are composed of stainless steel supports into which inserts can be placed (Fig. 3). The inserts are small cylindrical plates with a central hole of 4 mm diameter and allow the convenient testing of different materials. The supports are equipped with a double screen so as to protect the insulator wall against the discharge on the axis. The ferroelectric trigger disk and a bias electrode are located in the hollow cathode space. During the development phase the tube is sealed off by means of Al foil gaskets and an external clamping mechanism to allow easy access. The UHV and gas supply connection is provided via the cathode flange. For the test program described below the tube is filled with He.

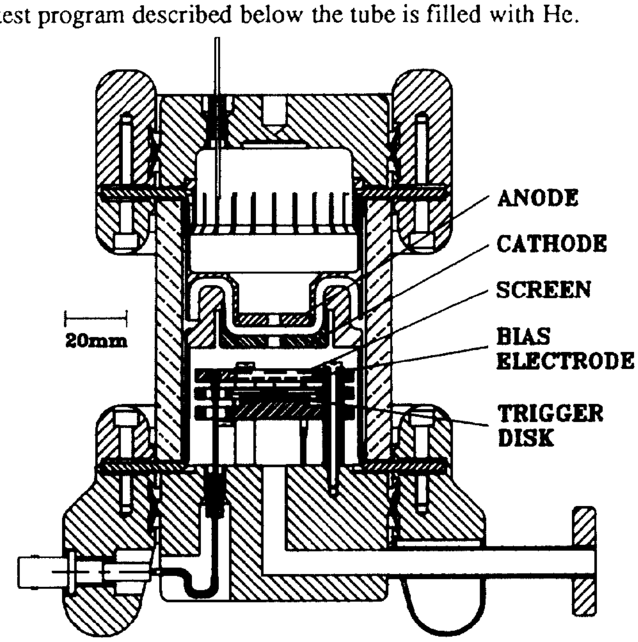


Fig. 3 Basic design of power switch

### *4.3 The ferroelectric trigger*

The switch is triggered by a pulse of about 2 kV applied to a 0.3 mm thick disk of ferroelectric (FE) material of 40 $mm^2$ emission area. Highest current emission (50 A) is obtained with PLZT material of composition 2/95/5 [4]. The emitted current is gas-amplified by a dc potential of 375 V applied to the auxiliary grid between trigger disk and cathode. This potential also improves considerably the hold-off voltage. A large trigger range from 150 V to 35 kV has been obtained, with a minimum jitter of 2 ns at a charging voltage of 35 kV. At the minimum operation voltage of 1.5 kV and a He pressure of 30 Pa, a jitter of <30 ns is obtained, acceptable for our application. The self breakdown voltage at this pressure is about 40 kV, demonstrating well the strong emission capability of the PLZT disk. The trigger shows very good reliability and survived $10^5$ pulses at 10 kA and $10^4$ pulses at 30 kA without any sign of fatigue. These tests were performed in the high erosion environment of stainless steel electrodes with strong metal deposition on the trigger disk.

### *4.4 Electrode material*

Several electrode materials have been tested in order to find out the material best suited for our application.

Stainless steel electrodes were badly damaged after switching $5 \cdot 10^3$ pulses of 400 mC charge transfer per pulse. They are unsuitable for this application. Tests with high density graphite electrodes had to be abandoned after $5 \cdot 10^4$ pulses of 90 mC. Though the erosion damage was small, the rate of erratic discharges was high, presumably caused by graphite dust particles deposited on the insulator walls. Thoriated tungsten electrodes (2% $ThO_2$) survived $6 \cdot 10^4$ pulses of 90 mC with very low erosion and no sign of performance deterioration. Thoria additions increase the high temperature strength and recristallisation temperature of tungsten. This material has been retained for our application.

### *4.5 Annular electrode holes*

Current density and erosion rate can be reduced by increasing the electrode hole diameter. This affects however adversely the hold-off voltage. Electrodes with ring-shaped holes can overcome this difficulty. Preliminary tests with ring holes of 14 mm diameter and 2.5 mm width gave very encouraging results. The discharge covers homogeneously the ring surface, thus decreasing considerably the current density. For stainless steel electrodes tested with 30 kA / 400 mC pulses a lifetime of about $10^4$ discharges was obtained as compared to $5 \cdot 10^3$ pulses using a cylindrical hole geometry.

### *4.6 Quenching and switch resistance*

In a narrow range of comparably low discharge currents operation is perturbed by frequent current interruptions called "quenching" after similar observations in thyratrons at high current and long pulse duration. Whereas quenching is fatal for thyratrons, probably due to electrode damage following transition from a glow discharge to a metal vapor arc, the hollow electrode switch operates also above the quenching region and even up to 50 kA in a (diffuse) superdense glow mode of comparably low energy density and electrode erosion. This is confirmed by the high on-state resistance and the absence of spark marks on the electrodes. The on-state resistance using annular hole stainless steel electrodes is about 25 mΩ at an amplitude of 10 kA and the pulse shape of Fig. 1, decreasing to 14 mΩ at 25 kA and to 10 mΩ at 50 kA. For stainless steel electrodes with a cylindrical hole of 4 mm diameter the on-state resistance is about 30% lower.

With ring hole electrodes the quench region is shifted to a current of <1 kA as compared to up to 8 kA for cylindrical hole electrodes. These values are below our operation currents so that quenching will not perturb the operation.

## 5. CONCLUSION AND OUTLOOK

The development program of the FE triggered hollow electrode switch has given the following very encouraging first results:

- The high trigger power of the FE disk provides an unprecedented voltage operation range of more than 100, covering well the beam momentum range of the LHC and allowing operation far below the self breakdown voltage.

-The FE trigger operation is reliable and does even not deteriorate in a strong erosion environment.

-The annular hole geometry decreases the erosion rate, improves lifetime and eliminates for this application the quenching problem, which is shifted to very low currents.

Our development work is actually pursued in 2 areas:

-A 350 °C in situ bakeout facility is under construction to investigate the gas reservoir issue.

-A 2-gap version is under study. Preliminary results show that at 30 Pa and with a trigger disk for each gap a ratio $U_{self\text{-}breakdown} / U_{max} > 2$ can be obtained. This may be sufficient for obtaining the required low rate of untriggered discharges.


## ACKNOWLEDGMENT

This development program profited much from the experience and inventiveness of the late Helmut Kuhn who designed the first versions of the switch and has defined most of the tubes technological characteristics.


## 6. REFERENCES


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