IPP-Report

Max-Planck-Institut für Plasmaphysik

Th. Franke, R. Blokker, G. Lexa, W. McGlaun, A. Moosbauer, R. Zultner (IPP Garching)

E. Ramezani, R. Leutwyler, S. Gekenidis, A. Welleman (ABB Switzerland)

A New 80kV / 14kA Solid State Thyristor Crowbar for the Commissioning and Testing of Vacuum Power Tubes in Fusion Research at IPP Garching

IPP 1/343
January, 2012

Abstract

When testing power vacuum tubes, it is very important to be careful and to protect the device being tested under all circumstances from any damages. It is necessary for the first test to be passed with non-destructive measurements as well as with full power tests up to several megawatts, which may be destructive in a few microseconds if the protection system should fail, e.g. in the case of an internal arc at such a device. For that reason, the necessity of an active trigger-able, fast switching and highly reliable solid state crowbar protection system arose for the tests of the tubes in the test bed before they are to be installed in the main experiment ASDEX Upgrade or other experiments at IPP Garching, mainly for the additional heating systems to switch and regulate the high voltage with high power. When testing power vacuum tubes for fusion research such as Thales CQK200-4A, the main goal is to find out if the tube operates within its specifications.

The paper describes the changeover from a mercury ignitron to a solid state protection crowbar on the test bed for the commissioning of the power vacuum tubes for the use for additional heating systems at ASDEX Upgrade (such as ECRH, NBI or ICRF and other experiments at IPP Garching).

Contents

1. Introduction

When dealing with power vacuum devices, such as tetrodes, which are installed in several fusion experiments all over the world as well as at the IPP Garching, it must be considered that these are devices which are made in difficult processes with a lot of mechanical, chemical and heat-treated parts, built with modern manufacturing machines and partially in handmade processes. Moreover, really rare materials like rhenium or slightly radioactive materials like thoriated tungsten are used for manufacturing. Furthermore, the tubes have to be heated and to be evacuated to a high-vacuum, which leads to mechanical stresses in the material and other effects. In the end the tube can be regarded as a complex shock sensitive system and it has a preferred position. Additionally, the individual behavior arises in the later operation of the tube because of the variation of several parameters which are defined by the tubes manufacturing process and the influence of the operational values, as there are filament-emissions, high voltage characteristics of the surfaces, X-ray emissions, space charges, secondary electron emissions and many more. The complexity can be seen when regarding the amount of possible influences to such a power vacuum tube.

Therefore, a high amount of experience is necessary for the correct application of the tube. But if the latter said is assured, then the tube is a highly reliable and long-living device, e.g. for switching and regulation of the high voltage of the additional heating systems. The use at IPP Garching is as a linear fast switching regulator, which also means high power dissipation. The cooling has effects on the safe operation area and especially on the thermal stability. If the tube is overheated, many unusual things may happen, such as deforming of the anode or grids, or the flashing over because of melting particles or surfaces which change their roughness. So the main point is to keep an eye on all such influences at a glance. Therefore, the vacuum devices are used and well-known only by highly experienced specialists, who mostly took over their knowledge from the former generation of engineers and technicians, that´s why it is important for the people to speak about and exchange their experiences in order to have a common database. And in the future it will be much more important to do so because the market for tubes is changing into a niche market, where solid state solutions have too many disadvantages or are even not able to work with the possible high parameters of such power tubes. This can be because of the high frequencies connected with high power (e.g. MHz with MW) or really high power densities. Here, we are talking about several MW which can be operated in a tube volume of not more than one cubic meter (only the tube alone without power and auxiliary supplies).

The trend is going more and more to combine the advantages of the tube with new and modern electronics, switching power supplies for the screen grid instead of linear regulated ones, or to get rid of heavy 50Hz-filament transformers for the filament, or solid state drivers for the control grid instead of tube based types. The modern automation opportunities such as standard PLCs combined with high-speed PLCs [6] based on FPGAs for fast switching or Microcontrollers help control the tube´s environment, such as water cooling, insulation gas systems, overvoltage protection, overcurrent protection and others. In that manner, sometimes the step from one technology to another isn´t easy and sometimes very bumpy because a lot of details which have to be considered and the sometimes surprising results yielding, when theory seems to be easy, but the reality quickly shows the opposite when such a modernization is carried out in a practical way. At the end, the result recompenses the efforts and money which were invested in order to reach new quality steps on the advancement to a better world.

Under these aspects, IPP Garching decided to take the step to replace the protection system, which was a former mercury ignitron crowbar switch, with a new solid state crowbar protection system [2], [4], [5]. The aim was not only to exchange it, but to find a highly reliable device, which is in all points better than the ignitron solution. This means, e.g. switching time, reliability, triggering with passive triggered circuit (well-known for the physicists) but moreover with an active triggered circuit, which is totally independent, a fail-safe trigger circuit which protects the tube even if the mains supply or optical trigger should fail, a testing with high voltage, which is at least 50% higher than the operation voltage, a current reversal opportunity and a peak current, which allows in total a short-circuit of a power supply with several megawatts output power.

The concept should be modular, so that the operating voltage level can be changed when using more or less stages easily up to the required voltages. At IPP Garching, there are mainly three voltage levels for the additional heating systems; there are roughly at 35kV, 70kV and 120kV. Moreover, the aspect of the lifetime should be regarded. The market has abundant solutions in the similar specifications range. The limitation of the lifetime from professional discussions added with the working principal constrains us to limit the number of discharges. In other applications it was limited to a few dozens, which seemed to be too small. And hence our limit was set to greater than 10.000.

As mentioned above, the power vacuum tube is not merely a simple device, and the damage or loss of a tube is to be prevented under all circumstances; that´s why the new solid state crowbar had to be tested extensively. Otherwise, if not working properly, it could damage the tube,. On the other hand, each such test is combined with money and personnel expenses, so that a good strategy and planning is necessary as a basis of success.

What well-known is that when switching high power and high voltage happens quickly or it is modulated with a high frequency, then the electromagnetic influences have to be considered from the beginning of the design – otherwise the price for modifications and test costs can easily explode and burn up the budget.

2. Configuration of the tube test bed

The test bed is supplied from the central high voltage power supply, which delivers a roughly pre-regulated voltage (several kilovolt drop is possible over several milliseconds when the load is switched on and off). Then, the actual value can be stabilized within a few milliseconds to a few hundred volts. The fast switching off is not possible because for filtering at the output there is a large capacitor bank which stores the energy. The current from this mainly ABB- or Siemens-thyristor controlled power supply flows through a long triaxial cable (about 100 m) to the test bed.

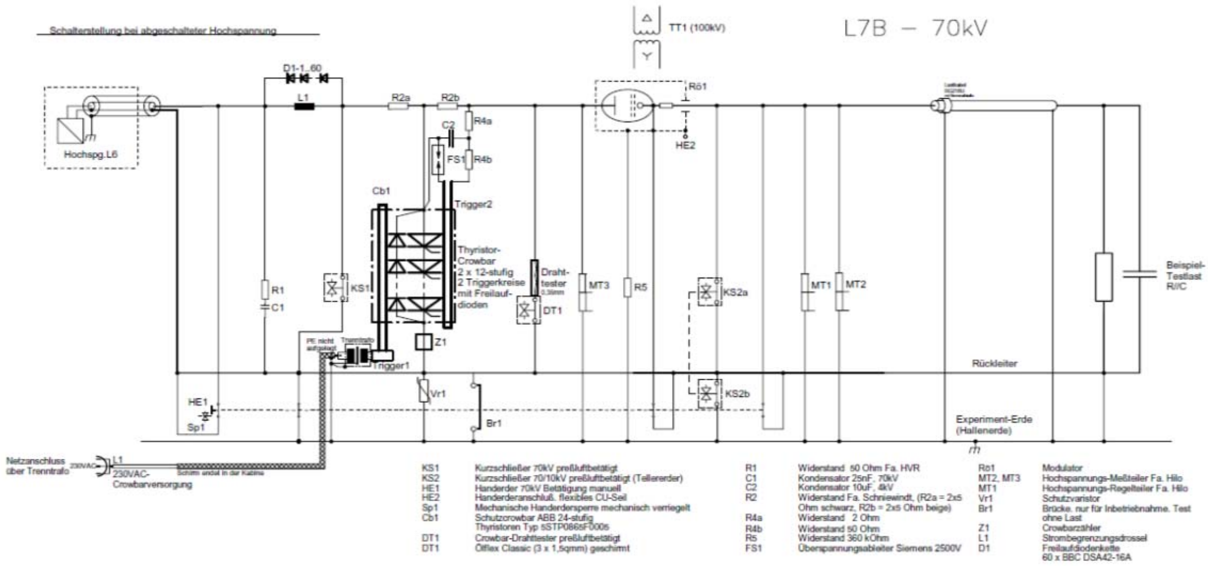

Figure 1: Principal schematic drawing of the vacuum tube test bed (with RC-dummy load)

The current then flows into a small (80 microhenry) inductor, to decrease the rise time of the current for hard switching, besides having a freewheeling diode. In [11] 80 uH were used as well. The inductance was calculated from the maximum di/dt which the thyristor-elements accept. The inductance is very low as compared to other crowbar systems, e.g. [10] mentions 400 uH.

The current then flows through two large damping and limiting resistors (where the crowbar is connected) on to the power modulator, where the vacuum power tube is situated. This tube is a CQK200-4A from the Thales Company, former Thomson (the CQK200-4A is a modern derivative of the former CQK200-4 after take-over from ABB, BBC and a first tube design from AEG – Telefunken). The above-mentioned damping resistors (both 10 Ohm) are divided in two resistors because the first resistor damps the current in the case of the switching of the crowbar, the second resistors can work as a passive trigger because rising currents can within a short time lead to a higher voltage at this resistor until a special passive trigger circuit is activated and thereby it triggers the crowbar. The second resistor also decouples the tube circuit with the load from the protection circuit. That is necessary because the current has to commutate in the case of an arc in the load and the tube to the protection circuit with the crowbar; this is only possible if the resistance in the protection circuit is lower than the shorted circuit. The second resistor therefore gives the warranty that the impedance of the crowbar can never be higher than the short since this impedance is always added to the short and is from the beginning chosen to be higher than the crowbar impedance. It is evident that in these resistors the peak power dissipation increases during a pulse up to 100 kW at 10 Ohm and 100 Amperes. But during the normal pulsed operation of ASDEX Upgrade (usually 3 seconds, maximum 10 seconds every 10-15 minutes) there is nearly no average power with about 100 W because of the low on-off-ratio. In [11] a crowbar with two 2 Ohm resistors is shown, which seems to be enough and would drastically reduce the peak power of the resistors. This still has to be investigated under IPP conditions. It has to be considered that a reduction of the resistance value has to be verified in each application, e.g. with a wire-test as a short because a lower resistance increases the faulty energy in the circuit.

Moreover, the circuit consists of an RC-damping element to prevent fast spikes which could lead to over voltages with the result of arcing.

There are switches for grounding and earthing of the test bed for safety reasons. There is a wire-tester for the crowbar which works as a short circuit in the case of activation; here a wire with a diameter of 0.35 millimeters and a length of about 0.6 meters has to withstand the test, if the crowbar reaction time is fast enough to take over the short-circuit current which flows in the wire in the beginning; if not, the wire will explode [7]. This test is especially necessary to limit the energy, which is dumped in the short circuit, thus preventing, e.g. great damages in the loads like gyrotrons or neutral beam ion sources (which are normally connected to the output of the modulator). In the case of the test bed, a resistive – capacitive load works as a dummy load. The load can handle the energy and would not be destroyed, if there were no crowbar available, but the vacuum power tube in the modulator could be hardly damaged. It never happened with the new crowbar system.

Photo 1: Test bed for qualification of vacuum power tubes: Modulator (left), wire tester (in front of the modulator), damping and triggering resistors (middle), solid-state-crowbar (right), high voltage divider oil transformer for the modulator (right behind the crowbar)

It should be mentioned that the new solid state crowbar is built up without any housing, which can be seen in the photo. This leads to a little contamination with dust. The only necessary maintenance is, therefore, to clean it from time to time. A cover is to be designed for an atmosphere that is very dirty, but we do not have such an atmosphere. The cover would otherwise consist of an axial divided cylinder of Macrolon® around the device with a plate at the top which can be screwed together with some plastic bolts. The two segments are necessary in order to have an easier access to the device if necessary. As thermal heat can develop during frequent switching or when applying a high voltage for a longer time, it is then recommended to have some air openings in the cover to allow natural convection.

3. Description of the new solid state crowbar system

The crowbar consists of 24 stages, whereby every stage has one ABB-thyristor. There are two insulated trigger circuits: one can be fired actively by a fiber optic and the other is fired passively if an overcurrent occurs. Both trigger circuits have advantages and disadvantages, so the combination is the most reliable solution. The trigger box for the active circuit is equipped with a complex programmable logic device and has an optical trigger input and an optical status feedback output. The principal circuit of the application can be seen in the schematic below.

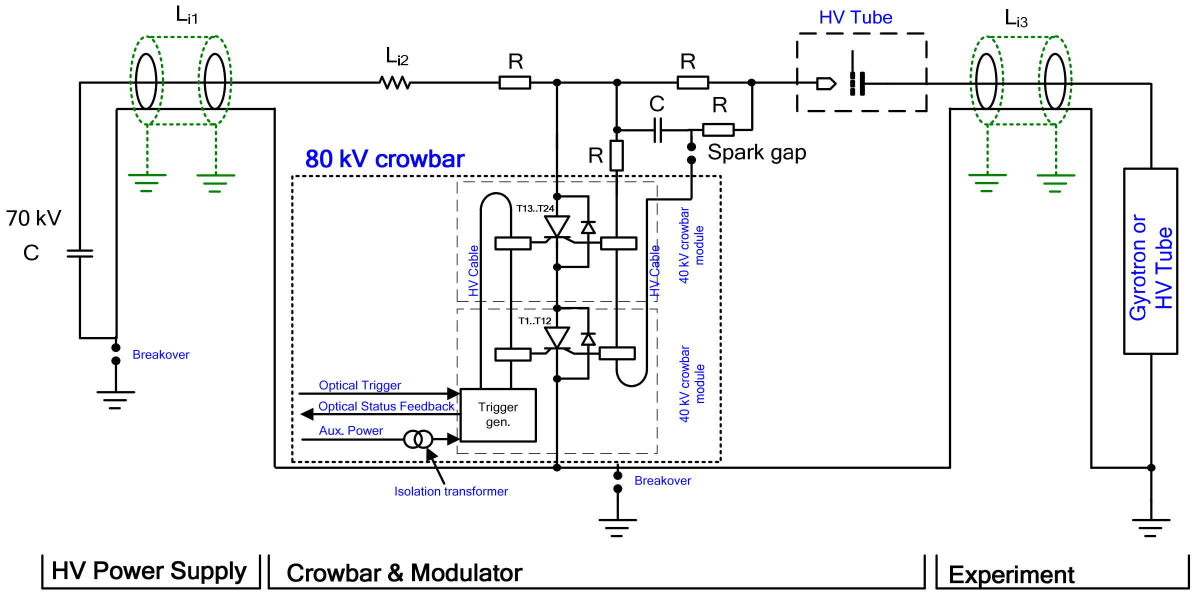

Figure 2: Principal circuit of the crowbar (on the left hand side only the output capacitor of the thyristor controlled power supply is illustrated - to simplify the drawing)

Each stage is equipped with a resistive-capacitive chain that is used for the static and dynamic voltage distribution over each of the 24 stages; moreover a break over diode (BOD) was implemented, so that the thyristor will be fired in any case with an active pulse at the gate and not with the notorious overvoltage from cathode to anode, which can destroy the device because of the hot spot formation within the silica wafer. As can be seen from the figure below, the voltage distribution and protection is completed with a freewheeling diode which protects each stage thyristor in the case that a current reversal occurs. Normally it was provided in the measurements, but it may occur when the current is circulating, which occurs in LRC-resonant circuits, e.g. when a capacitor bank is discharged in an inductive load [3], [8] (which can lead to such a damped, but circulating current waveform) and could also destroy the device. The freewheeling diodes may prevent this optimally.

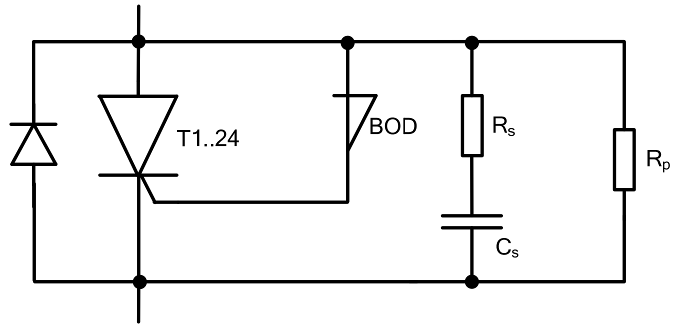

Figure 3: Protection circuit for overvoltage, current reversal and voltage distribution at one stage

Now it is necessary to explain in detail the two trigger circuits. The passive trigger circuit is the main normal circuit at IPP for all ignitron crowbars today. Some older ascertained ignitron crowbars at IPP were triggered actively with two redundant trigger circuits. Now with these two trigger circuits we have a mixture of both because both have advantages, which we wanted to utilize.

First we should observe the passive trigger because it works even without any auxiliary supplies and without external control or trigger signals. In the case of an arc, the current through the two resistors rises. In parallel with the second resistor there is a capacitor, which is charged by the voltage across the resistor. A chain of a spark gap, a damping resistor and a high-voltage cable (without shielding) - which is the trigger cable and is led through all 24 stages - is connected to the capacitor. If the voltage of the capacitor reaches the pick-up voltage of the spark gap, the crowbar is triggered since the capacitor discharges itself through this chain. The result is a trigger pulse to each stage, which is coupled out with ring core transformers for every thyristor stage. When changing the spark gap to other pick-up voltages, the trip current can be changed. That's why the disadvantage of the passive trigger is that it works only at a non-remotely alterable current trip level. The other disadvantage is that the pick-up voltage of the spark gap changes with each event; this may be slow, but degrading the spark gap voltage continuously, so that the trip level is not accurately adjustable and even may change to higher values, which can be dangerous. Another problem is that during modulation, the voltage of the tube modulator or when fast switching on the modulator, the inrush current can reach values up to 200 A, which is about the maximum emission capability of the cathode of the tube, so that the passive trigger would switch on, when the level would be too low and to close to the operating current (which is at most 90 A). So the practice is to use a current trip level, which is about two to three times higher than the normal operating current and somewhat higher than the inrush current, usually 300 A. This leads to the problem that the passive trigger never switches, in the case that the vacuum power tube has an internal arc, but not the load (e.g. with resistive load). This would lead to an uninterruptable failure because the tube shows no reaction anymore to the control and the current cannot be switched off fast enough.

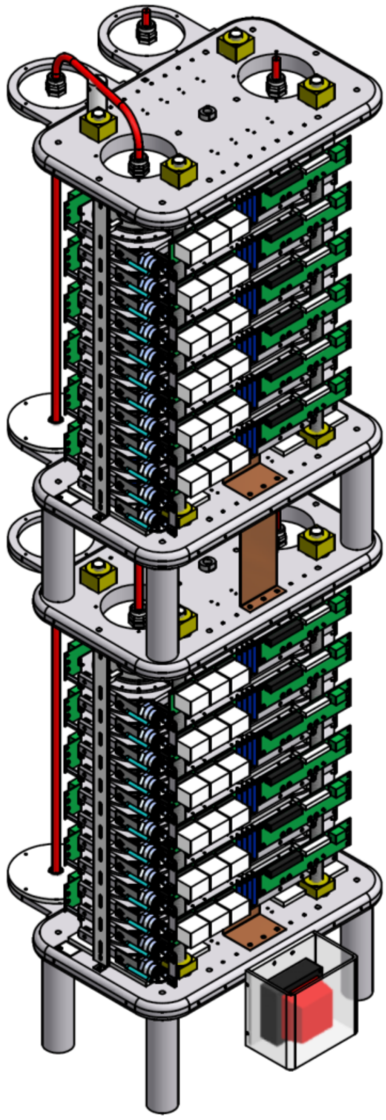

Figure 4: Crowbar with the insulation transformer (red box) and the trigger-box behind (not visible)

To prevent this, the second active fiber optic trigger circuit is used. This allows (by means of an arc-detection-system) the triggering of the crowbar, which then stops the current flow through the tube and the load. The arc-detection-unit was developed at IPP and it works reliably, it detects the arc directly in the tube modulator without measuring the load current by fast observation of the grid voltages. The arc-detection-unit works within a microsecond and activates an optical trigger output, which is connected directly to the optical trigger input of the crowbar. Moreover, it is possible (with a built-up optical signal splitter) to use a second trigger output to trigger the same single input of the crowbar by means of other event handling systems.

In summary, the crowbar is best equipped with the combination of the active and passive trigger for all demands.

4. Commissioning experiences with the new solid state crowbar

The new solid-state-crowbar has been working until now without any damage or permanent failure. The only two problems were an EMC-disturbance, which could be solved really fast, and secondly a functional problem in the logical control; both were electronic failures in the trigger-box.

The first problem, (the EMC-disturbance) was solved with the following changes:

- implementing of a connection from the electronic PCB inside the trigger generator of the crowbar to the housing

- using an insulation transformer with two shields and usage of a shielded mains cable to the crowbar
- implementing a freewheeling diode over the di/dt limiting inductance at the high voltage input

The second problem, (the functional problem) was solved with a changing in the program of the programmable logic device (PLD) of the trigger box. The problem happened in a measuring-pause, where the external trigger generator was delivering trigger pulses over a longer time. The trigger box was thermally overstressed and this led to a failure. Normally it is not usual to apply such pulse-train over more than one hour with a few Hertz, but for test-purposes it was applied and not switched off. Although that such overstress never appears in the real application, the PLD was reprogrammed to observe and to stop such “illegal” triggering.

With these changes, the further operation and testing of the crowbar-device was successful. In the meantime, more than 100 events could be handled by the crowbar. The events were counted with an event counter that records only high current events. The event counter is a special so-called lightning counter from the Meteolabor Switzerland Company.

The following figure shows how the modifications solved the above mentioned EMC-disturbance.

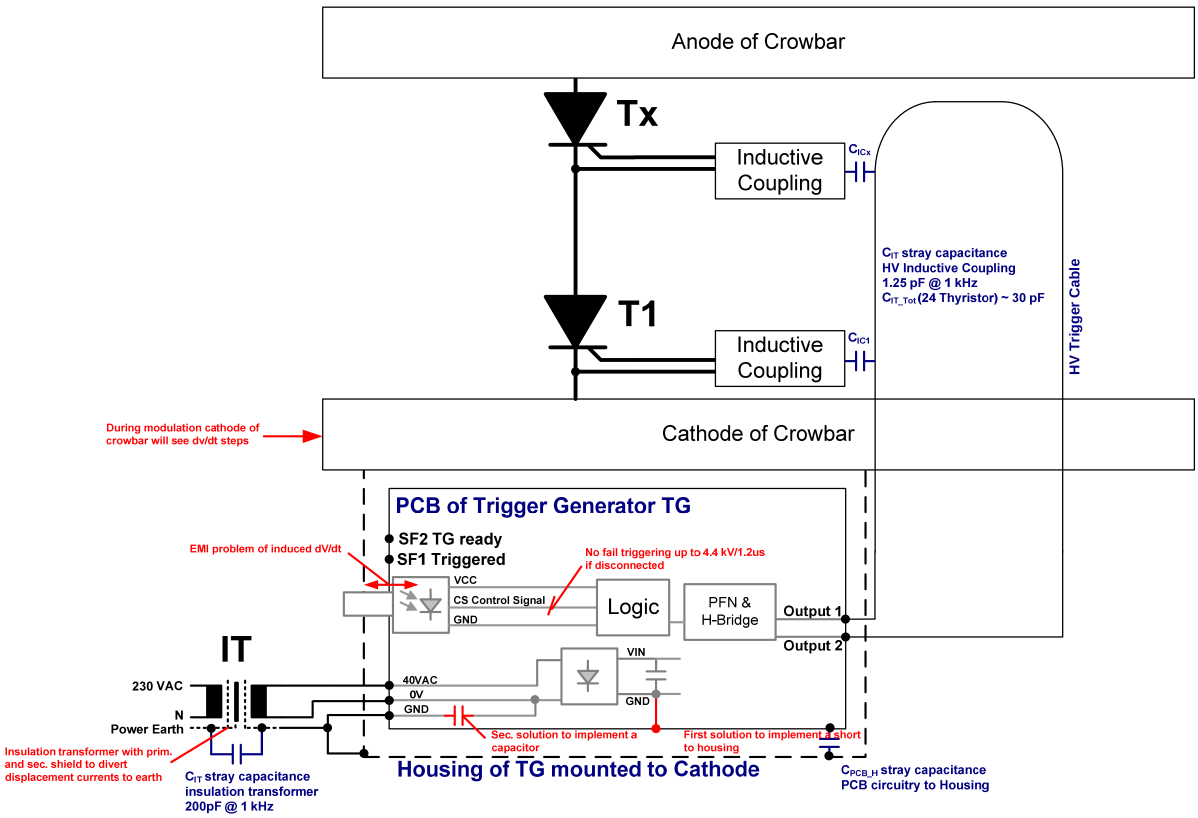

Figure 5: Schematic of the quality deviation report / ABB Switzerland

The following figures show how the modifications solved the functional problem.

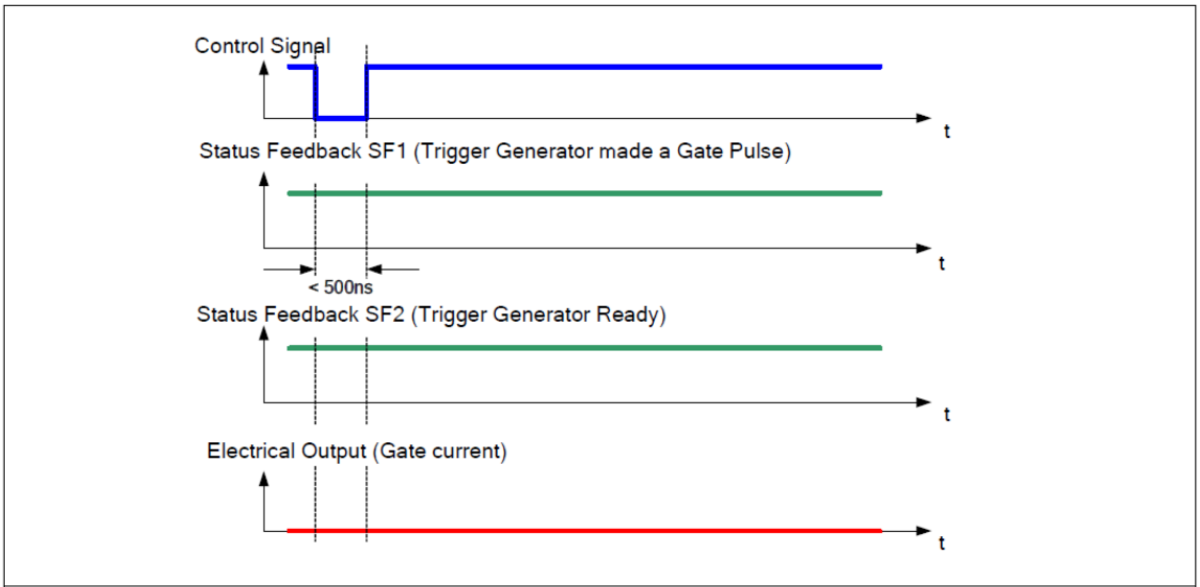

Fig. 1) Trigger pulse < 500ns

Figure 6: Timing of short trigger pulses

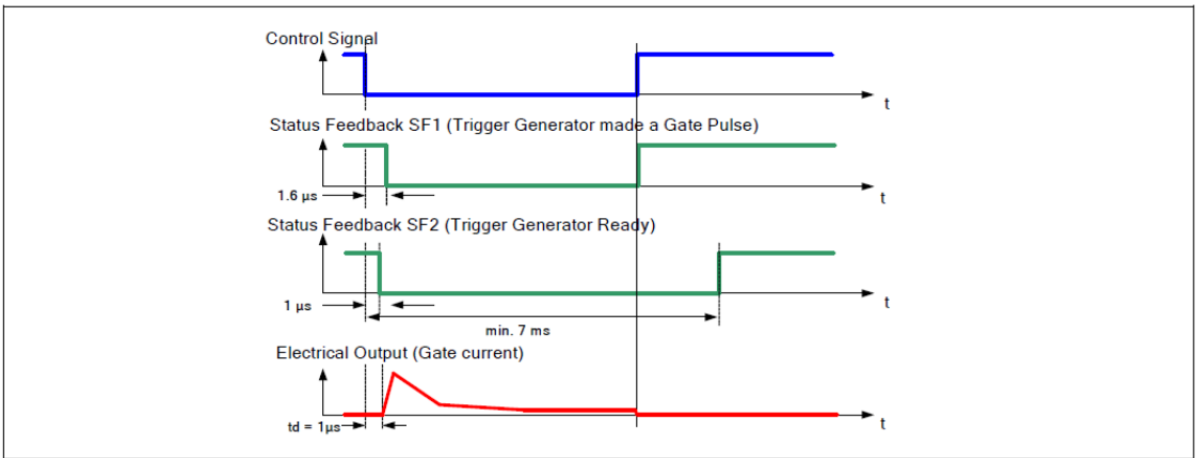

Fig. 2) Trigger pulse > 500ns

Figure 7: Timing of long trigger pulses

The commissioning of the crowbar was performed first only with wire tests and later with a new vacuum power tube, which was at IPP Garching at this time. The tube tended to arc. To investigate the tube, several operation points where measured, but if the tube showed arcing, in any case the new solid state crowbar protected the tube absolutely reliable.

5. Technical data of the solid state crowbar

	Min.	Typ.	Max.
Operation voltage DC			80 kV
Operation voltage DC withstand level for one minute			96 kV
Max. time at operation voltage DC			cont.
self-trigger per thyristor level (BOD)	4.0 kV	4.2 kV	4.4 kV
self-trigger voltage switch assembly (BOD)	96 kV		106 kV
Insulation voltage withstand level DC (HV-trigger cable connected to ground) for one minute (for this test additional BODs with 1000 V have to be added to each level to increase the self-triggering voltage above 120 kV)			120 kV
Leakage current at max. operating DC voltage		4.6 mA	5.6 mA
Peak current forward I_D			14 kA
Peak current reverse I_{DR}, tp=100 ms			30 A
Critical rate of rise of on-state current di/dt_{crit}			1200 A/µs
Repetition rate		1 every 15 min.	1 every 2 min.
Turn-on delay for the crowbar at 80 kV (From optical triggering to the time the voltage drops to 90%)		3.5 µs	
Turn-on delay for the crowbar at 10 kV (From optical triggering to the time the voltage drops to 90%)		4.5 µs	

6. Measurement Results

The measurement showed a good comparison between the predicted and realized values. The high peak current was measured with a Pearson-probe 301X (50 kA, 5 Hz - 2 MHz), the voltage was monitored with a Hilo-Test high-voltage divider HVT160RC (160 kV, <50 ns rise time). The new solid-state crowbar worked very well under all circumstances after the mentioned modifications. In the meantime the really fast switching and the easy control made the solid-state crowbar to a workhorse. The two trigger-circuits (active and passive) give a high security for the vacuum power tube and for the load connected to it, which is momentarily a resistive-capacitive load only, but can be later a high sensitive device, e.g. a Gyrotron. The current and voltage plots are showing that the crowbar reacts really fast. The energy handling capability is high and the warming of the electronic components of the crowbar never reached a critical value after the above-mentioned modification of the trigger box.

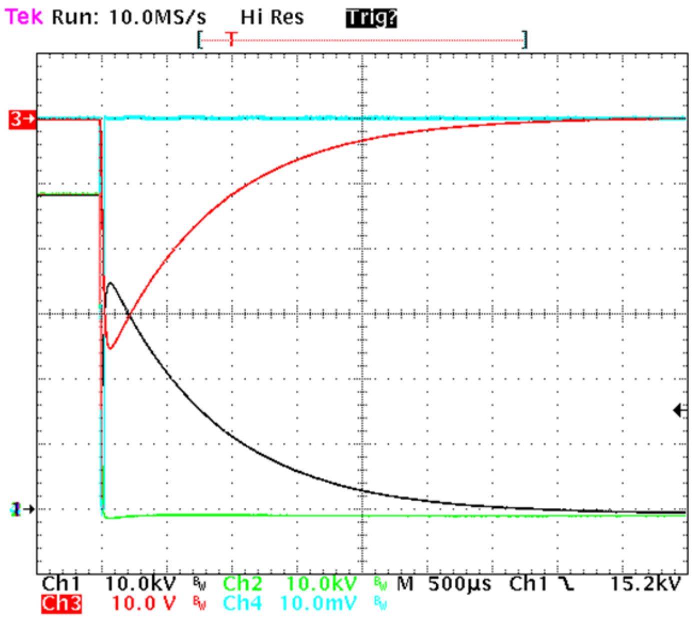

Figure 8: Ch1: input voltage (in front of the first 10 ohm resistor), CH2 crowbar voltage CH3: crowbar current (10 V≙1 kA), CH4 active trigger-signal

The current flows for a relatively long time (3 ms), as can be seen from the measured plot. The reason is the time-constant of the discharging circuit (10 Ohm before the crowbar together with the capacitor bank of 165 µF). But it is obvious that the anode voltage of the crowbar immediately goes to zero. The next plot shows this in more detail.

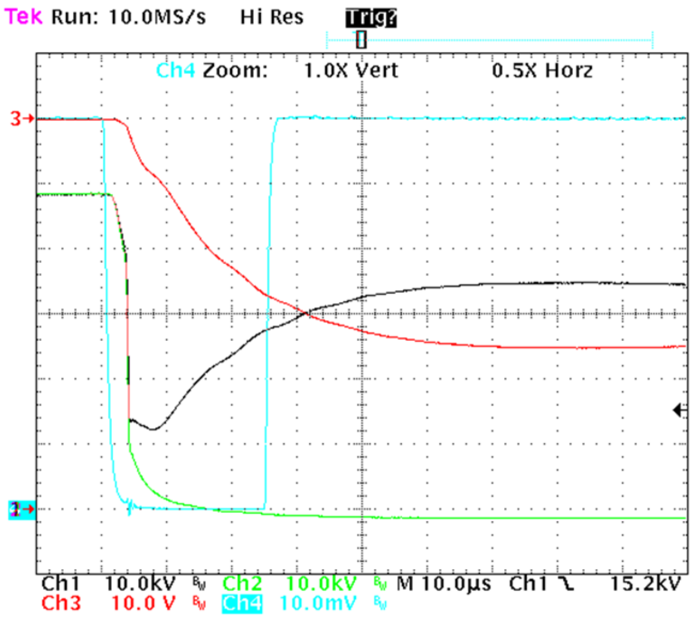

Figure 9: Ch1: input voltage (in front of the first 10 ohm resistor), CH2 crowbar voltage CH3: crowbar current (10V≙1kA), CH4 active trigger-signal

The Input voltage is about 46kV in this example, the current goes up to 3,5kA. The delay from the trigger signal to the falling edge of the crowbar voltage is about 4 microseconds and therefore really fast for this application.

Photo 2: New 80 kV, 14 kA two stage solid state crowbar with two independent trigger circuits (passive and active over fiber optic) [1]

7. Conclusion

For one year the new crowbar has been successfully used in the test bed now. Because of a lot of tests with partly difficult vacuum tubes which tended to flash over, the crowbar fulfilled already over one hundred discharges and this without any failure or degradation. Without the new solid state crowbar, the tested tubes would have already been destroyed several times.

The new solid state crowbar is nearly maintenance free, only cleaning from dust is recommended. The crowbar is fitted with two independent trigger circuits, an overvoltage protection and freewheeling diodes and is, therefore, best prepared for the use in research for the protection of vacuum tubes.

Compared to ignitron crowbars, there are some benefits of the solid state crowbar (e.g. the mercury-free operation, the constant turn-on delay time, which is nearly independent from the operating voltage and is only a few microseconds long).

The exchange of the new solid state crowbar in one of the real ASDEX Upgrade experiments is not planned yet, but hopefully we will already use the mercury-free new crowbars in one of the next projects. The new crowbar can then show its advantages after well and already longtime tested conditions at the vacuum tube test bed.

The crowbar is now ready and well proved for the next step: to extend it to 120kV, which means that a third stage has to be added and the trigger circuit has to be checked and if necessary optimized for the higher test voltage. This is a new challenge compared with [9].

It should be mentioned that the cooperation between ABB Switzerland and IPP Garching was really convenient and always open and trusty for transferring information from one party to the other, which at the end led to this good technical result.

8. Acknowledgement

The authors would like to thank Dr. Stäbler, the former head of the NBI-group at IPP Garching and Dr. Stober, the head of the ECRH-group at IPP Garching and Mr. Greuner from the GLADIS test facility for advice and financial support and the electrical workshop of Mr. Ogasa and the electronic workshop of Mr. Beibl and their staff for their practical assistance.

References

[1] ABB short form catalogue 2010 High Power Semiconductors ABB

[2] Solid State Switches for Pulse Power Modulators, Welleman, Waldmeyer, Ramezani, ABB Switzerland, Proceedings of LINAC 2002, Gyeongju, Korea, pp. 707-709

[3] A Study of High-Power Switch With Thyristor For Pulse Power Applications, Song, Yang, Oh, Cho, Namkung, Proceedings of LINAC 2002, Gyeongju, Korea, pp. 199-201

[4] The 12 kV, 50 kA Pulse Generator for the SPS MKDH Horizontal Beam Dump Kicker System, equipped with semiconductor switches, Bondhond, Ducimetière, Faure, Vossenberg, European Organization for Nuclear Research, Geneva, Switzerland, 11. May 2001

[5] Welleman, Ramezani, Schlapbach, ABB Semiconductors AG, Switzerland, Semiconductor Switches replace Thyratrons and Ignitrons, 5th Modulator Klystron Workshop MDK 2001, CERN Geneva

[6] Franke, Kircher, Boolean High Speed SPS überwacht und steuert das Fusionsplasma am MPI für Plasmaphysik in Garching, SPS/IPC/DRIVES 2006, Tagungsband, VDE Verlag, pp. 395-403

[7] Test Wire for High Voltage Power Supply Crowbar System, Joseph T. Bradley III and Michael Collins, Los Alamos National Laboratory; John M. Gahl, University of New Mexico, IEEE 1997

[8] High-voltage and high-current automatic crowbar, Cliffe, Smith - Departement of Electronic and Electrical Engineering, Loughborough University UK, Brown – DERA (FH), Kent, UK, 2001 IOP Publishing Ltd.

[9] High Voltage Solid State Crowbar Switches, Welleman, Fleischmann, Pulsed Power Conference, IEEE, 2005, pp. 828-831

[10] 130 kV, 130 A High, voltage switching mode power supply for neutral beam plasma heating: design issues, Ganuza, Del Rio, Garcia et al., JEMA, 2003 Elseviere Science B.V.

[11] Development of a high speed crowbar for Lansce, Friedrichs, Lyles, Doub, Los Alamos National Laboratory, IEEE, 1998, pp. 3473 – 3475