FHCT SEB cross-section measurements at H4IRRAD and with cosmic rays and its influence to LHC abort system reliability

Viliam Senaj

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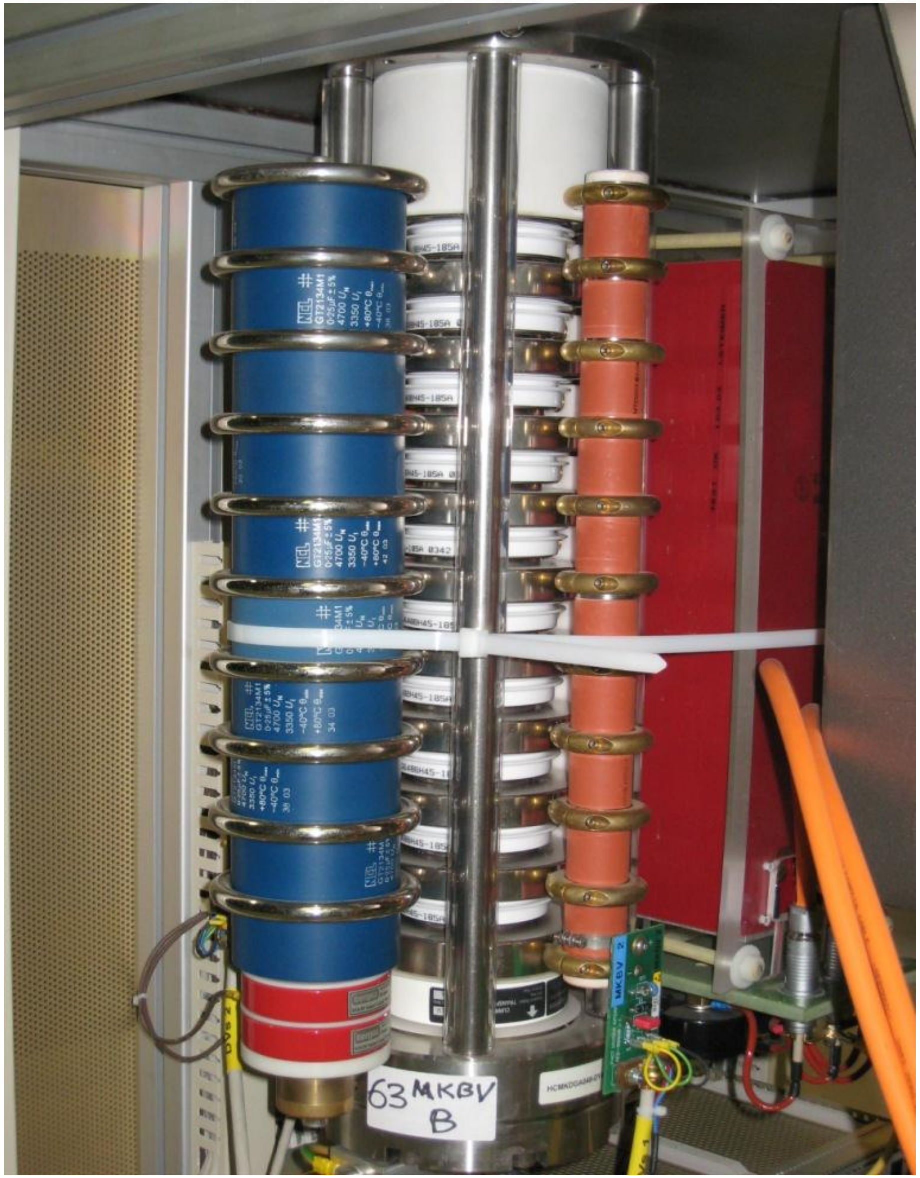
Motivation

- Crucial importance of reliable operation of the beam abort system for LHC security
- 30 MKD and 8 MKBH generators operate up to maximum voltage of ~ 29 kV at 7 TeV; 12 MKBV up to 16 kV at 7 TeV
- 680 FHCTs in MKD and MKBH exposed to an average voltage od 2.9 kV; up to ~ 3 kV on several devices expected (due to spread of voltage sharing resistors value and FHCT leakage currents)
- Generators are installed in UA63/67 and will see up to 10^6 $n.cm^{-2}.year^{-1}$ in axis of cable ducts according to simulations; radiation was ot expected in time of system design
- FHCT producers (Dynex & ABB) provide only basic SEB failure rate due to cosmic rays at sea level to be 100 FIT at 2.8 kV (1 FIT = 1 failure in 10^9 device hours); failure rate at 2.9 kV and 3 kV is unknown
- Failure of a FHCT will most likely provoke an asynchronous dump with associated beam loses and machine down time necessary for generator replacement and system re-calibration (~ 1 day)

FHCTs used

- ABB - 5STH20H4502
- DYNEX - DG648BH45-185
- Similar specifications from both producers:
  - Umax: 4.5 kV
  - Udc: 2.8 kV (100 FIT)
  - Imax: 80 kA
  - dI/dt: 20 kA/µs
  - Ileak: 10 µA @3kV
  - Load integral ~1.10^{6} A^{2}s
  - wafer diameter ~ 60 mm

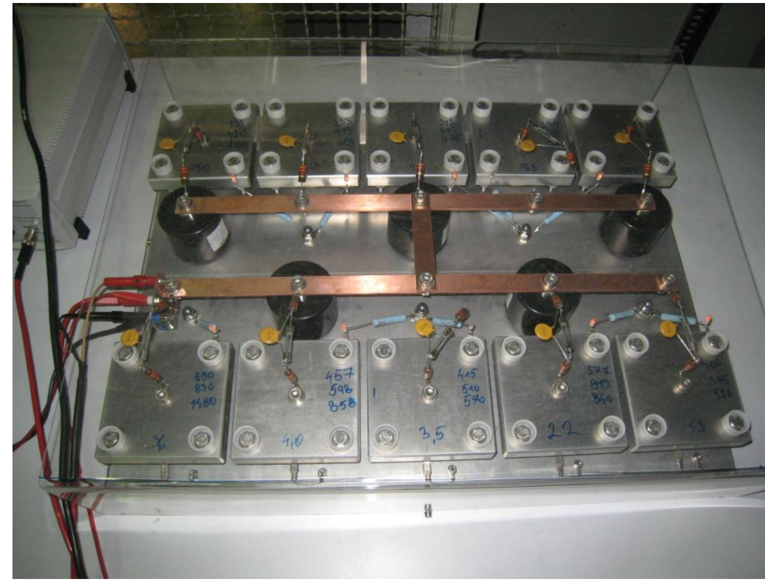


SEB failure rate estimation

- 680 FHCT with up to 6000 hours per year at maximum average voltage of 2.9 kV
- According to simulations the maximum fluence of 10^6 n.cm^{-2}.year^{-1} in cable duct axis is expected (7x of cosmic rays at sea level)
- From empiric observations - SEB failure rate increases ~ 10x for 7 % increase of the applied voltage; ~ 315 FIT at 2.9 kV; ~ 1000 FIT at 3 kV; expressed in SEB effective cross-section: $6x10^{-9}$ cm^2 at 2.8 kV, $1.9x10^{-8}$ cm^2 at 2.9 kV, $6x10^{-8}$ cm^2 at 3 kV
- Estimation of number of failures per year for 1/3rd of FHCT at 3 kV, 1/3rd at 2.9 kV and 1/3rd at 2.8 kV and an average neutron fluence equivalent to ¼ of the maximum simulated value gives 4 failures per year which is unacceptable
- Cost estimation if HV modification is neede: adding 2 FHCT into a stack. :
  - 156 pcs of additional FHCTs ~150 kCHF
  - 78 pcs new trigger transformers with 12 secondaries ~250 kCHF
  - Up-grade of stack mechanical and electrical parts (snubber capacitors, voltage sharing resistors, longer stack return rods) ~100 kCHF
  - 152 pcs of PTU and 72 pcs of HV PS - to increase the trigger transformer primary voltage by more than 20% (if improvement with new trigger transformer is insufficient) ~400 kCHF
- More accurate failure rate evaluation is needed in order to decide if HV modifications are necessary

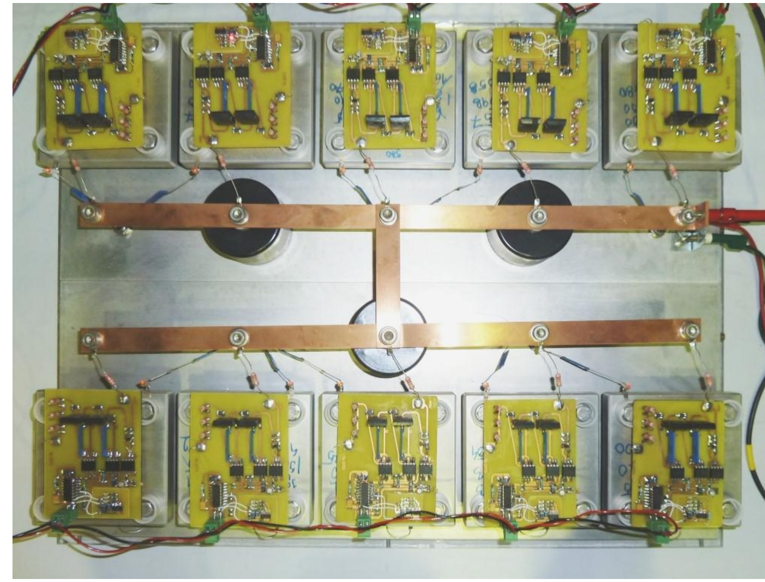
SEB test with thermal fuse

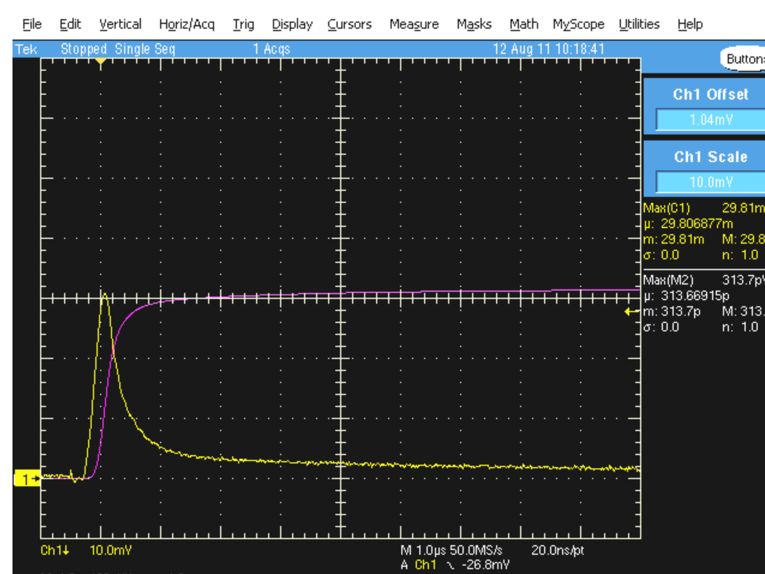
- SEB is a statistical process and accuracy of measurement of its cross-section depends on number of observed events
- Due to the FHCT price (~ 1 kCHF) and long lead time (6 - 18 months) our goal was to perform it in a less destructive way possible by limiting failure current and I^2t integral during SEB
- Simple limiting circuit with resistor and fast acting thermal fuse (62.5 mA) provided current limitation of 480 mA at 3kV and 650 mA at 4 kV; I^2t integral in both cases was defined by a melting property of fuse and was lower than 2.10^{-4} A^2s.
- Post SEB leakage current increase of more than 2 orders of magnitude observed and components became unusable for the application (request: Ileak < 10 µA @ 3 kV to keep voltage sharing accutracy).



SEB test with electronic limiting

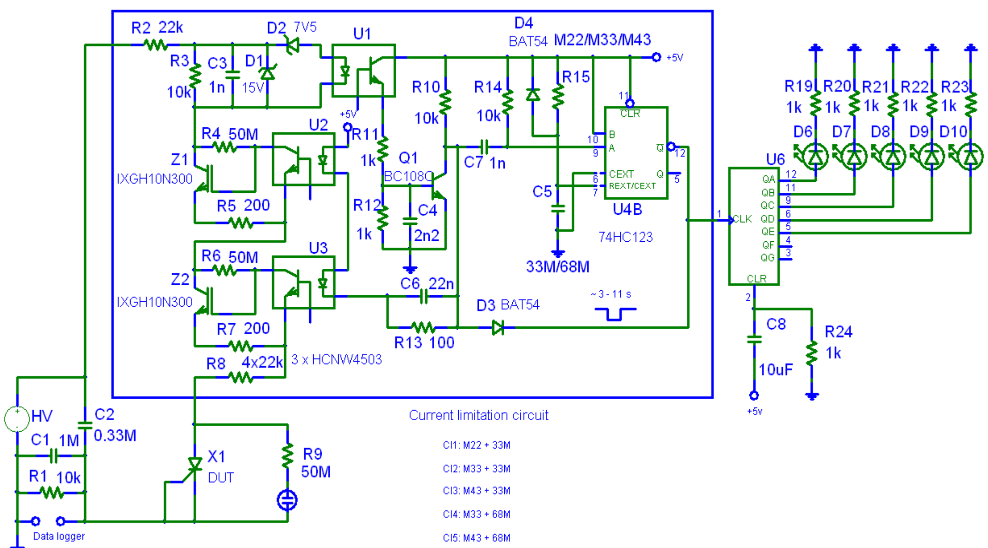
- Post-SEB leakage current increase most likely due to partial melting of semiconductor during SEB
- Reduction of deposited energy by fast electronic current limiting circuit with multifold function:
  - Short circuit current < 40 mA (10x less than fuse) and I^2t integral is < 4.10^{-10} A^2s (almost 10^6 x lower than fuse limitation)
  - Cut-off the voltage on FHCT (following SEB) lasting ~s to allow for remote SEB detection by low speed data recorder
  - Soft start with an average current limited to 0.5 mA if FHCT is in SC
  - Event number counter
- Tester consits of multiple FHCT in parallel with a current limiting circuit in series with each FHCT
- SEB is remotely detected as a temporary decrease of the assembly current consumption

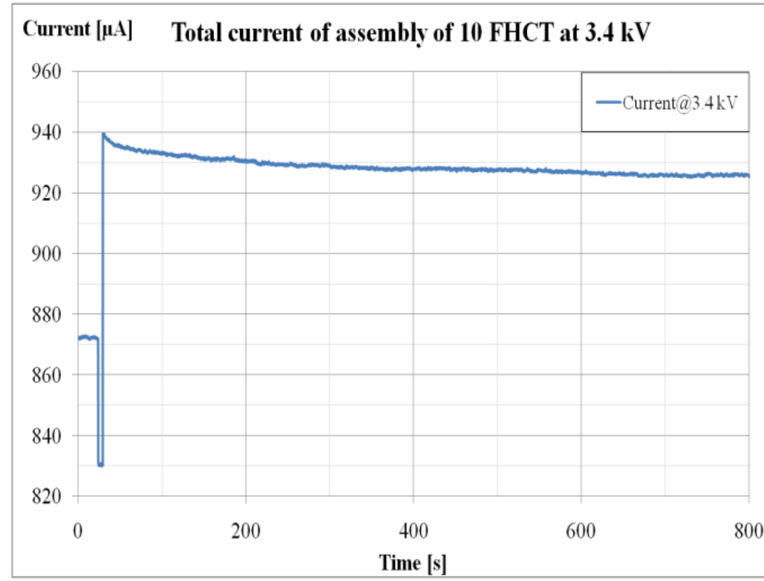


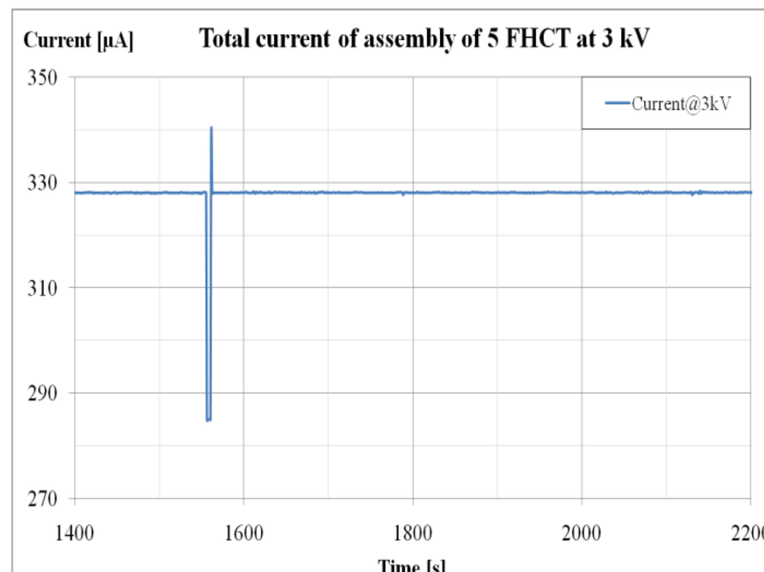


SEB test apparatus

- Leakage current increase after SEB at 3.4 kV with fast limiting installed is ~ 8x (compared to more than 100x with thermal fuse)
- At 3 kV we observe no leakage current increase after SEB
- Reduction of both energy delivered be HV power supply during SEB (fast limiting) and the energy stored on FHCT internal capacitance (lower test voltage) resulted in non-destructive SEB test







SEB measurement results

- Cosmic rays test done on 5 FHCTs of each family (DYNEX & ABB) at 3.4 and 4 kV
- Test at 4 kV lasted 156 h with the following results:
  - ABB: 1 SEB in 783 device hours
  - Dynex: 3 SEBs in 620 device hours
- Test at 3.4 kV with the following results:
  - ABB: no SEB in 20 000 device hours
  - Dynex: 6 SEBs in 19 500 device hours
- H4IRRAD test done with 5 FHCT from ABB. only 4 of them (all 4 from the same production batch- KV.xxx) experienced SEB and values bellow are valid for this batch
  - 2.6 kV: 1.58e9 HEH/cm2 – no SEB: SEB cross-section < 1.6e-10 cm-2 (insufficient statistics)
  - 2.8 kV: 8.84e8 HEH/cm2 – 3 SEB; SEB cross-section ~ 8.5 e-10 cm-2 (insufficient statistics)
  - 2.9 kV: 1.69e9 HEH/ cm2 – 6 SEB; SEB cross-section ~8.9e-10 cm-2 (insufficient statistics)
  - 3 kV: 3.41e8 HEH/cm2 – 15 SEB; SEB cross-section ~ 1.1e-8 cm-2
- Fifth FHCT came from different batch (GV.xxx) and did not experienced any SEB; its cross-section is hence much lower

Cross-section	4 kV [cm^2]	3.4 kV [cm^2]	3 kV [cm^2]	2.9 kV [cm^2]	2.8 kV [cm^2]	2.6 kV [cm^2]
ABB	~ 5.6×10^{-5}	< 2.2×10^{-6}	1.1×10^{-8}	~ 8.9×10^{-10}	~ 8.5×10^{-10}	< 1.6×10^{-10}
Dynex	~ 2.1×10^{-4}	~ 1.4×10^{-5}				

Abort system MTBF re-evaluation

- SEB cross-section at 3 kV evaluated reasonably accurately (15 SEBs)
- SEB cross-sections at 2.9 and 2.8 kV obtained with low accuracy; they were down-scaled from the value measured at 3 kV:
  - Cross-section of 3.6×10^{-9} at 2.9 kV (1/3rd of the value at 3 kV)
  - Cross-section of 1.2×10^{-9} at 2.8 kV (1/9th of value at 3 kV)
- Number of SEB related failures estimated under the same conditions as before (1/3rd of FHCTs at 2.8, 2.9 and 3 kV correspondingly), with average neutron fluence equivalent to ¼ of the simulated maximum (10^6 $n.cm^{-2}.year^{-1}$) and with ABB FHCT only is 1 per year (4x less than estimation based on producer data)
- If ½ of FHCT are Dynex and their SEB cross-section is ~ 3 - 6 x higher (based on cosmic rays measurement) then the number of failure will be 2 - 4 per year.
- In case of using the ABB FHCTs from production batch GV.xxx we can expect ~ 0.25 failure per year

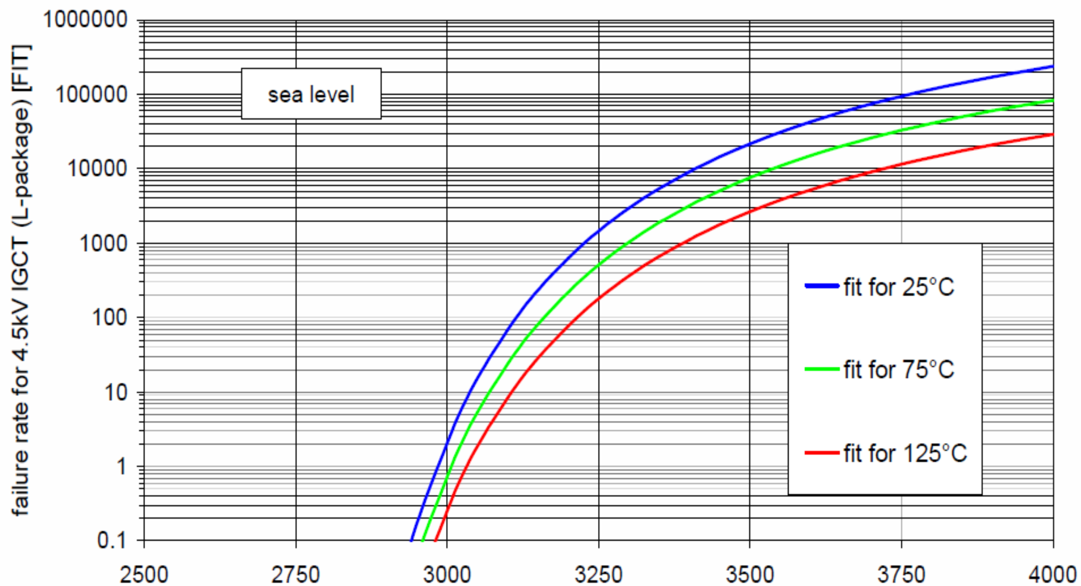
Conclusions - Recommendations

- Sensitivity of ABB FHCT much lower than expected – sufficiently low to not require modyfication of the number of FHCT in a stack
- Sensitivity of Dynex, Westcode and ABB FHCT (ABB production lot that did not experienced SEB during first SEB test) to be measured with reasonable accuracy
- Real neutron fluence in UA galleries will be evaluated after next TS (~ 1 month to evaluate integrating detectors)
- Generators at positions with higher radiation to be populated with ABB FHCT
- Increasing of FHCT temperature by 10 °C leads to 20% reduction of failure rate; further increase of temperature is still possible (up to ~ 30°C?) that will be favourable for eventual UA ambient temperature rise at high energy
- Better shielding of cable ducts is probably still possible

SEB at cosmic rays

- SEB failure rate due to cosmic rays expressed in FIT according to the formula below
- Producer does not provide parameters C_1- C_3 for our components; to be measured
- SEB failure rate depends on temperature as well; +10 °C leads to -20 % of failure rate
- SEB failure rate voltage dependence seems to be almost 8x stronger than expected: 100 FIT corresponds to ~3110 V; at 3328 V (7 % above 100 FIT) failure rate is about 7500 FIT instead of empiric estimation of 1000 FIT

$$\lambda(V_{DC}, T_{vj}, h) = \underbrace{C_3 \cdot \exp\left(\frac{C_2}{C_1 - V_{DC}}\right)}_{①} \cdot \underbrace{\exp\left(\frac{25 - T_{vj}}{47.6}\right)}_{②} \cdot \underbrace{\exp\left(\frac{1 - \left(1 - \frac{h}{44300}\right)^{5.26}}{0.143}\right)}_{③}$$



Single Event Burnout physics

- High energy ion, proton or neutron (by nuclear reactions: Si(*n*,)Mg, Si(*n*,*p*)Al [15], Si(*p*,2*p*)Al, Si(*p*,*p*)Mg) can generate e-h pairs
- If large number of e-h pairs (>3.10^5) are generated in a small volume (~ µm) in P/N junction depletion zone under high electric field (~ 10 MV/m for HV componennts), the electric field can reach a value sufficient for avalanche ionisation (> 36 MV/m)
- Due to low cross-section of such created conductive filament, resulting high local current densities usually leads to semiconductor melting and hence irreversible component damage