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CERN — SL DIVISION

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# THE QECD PULSE GENERATOR FOR FAST RESONANT EXTRACTION

# (QUADRUPOLE EXTRACTION CAPACITOR DISCHARGE)

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Geneva, Switzerland,
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# The QECD Pulse Generator for Fast Resonant Extraction (Quadrupole Extraction Capacitor Discharge)

J. Bonthond

## 1. Introduction

In the SPS two methods for particle extraction are used. One of these methods, the Slow Extraction, delivers extracted beams with a duration of up to several seconds. The other one ( Ref.1 ), the Fast Resonant Extraction, providing particle bursts with a duration of a few milliseconds, is also called Fast/Slow extraction and is used for neutrino experiments.

For this kind of extraction a quadrupole ( QE 3140 ) is installed, which is connected to a high voltage pulse generator ( QECD ) delivering quasi-trapezoïdal current pulses.

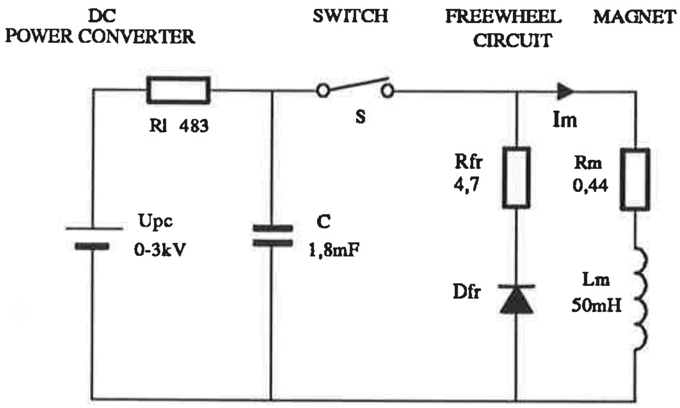
Originally ( Ref.2 ) Fast Resonant Extraction was obtained by exiting a quadrupole with a current pulse having a triangular waveform.
The beam is pushed onto resonance at the rising slope of the pulse and after a few milliseconds the resonance is stopped at the falling slope.
During resonance, particles resonating in the horizontal plane with a sufficiently high amplitude, enter the extraction channel and leave the SPS.
The "spill" ( i.e. the number of particles extracted per time interval ) of a beam extracted with such a triangular current pulse has an approximately Gaussian structure.

Because a more rectangular spill structure is better suited for the experiments, a generator delivering current pulses with a quasi-trapezoïdal waveform was developed.
The current pulses have a rising slope with 2 different gradients, of which the second one is approximately zero.
In addition, new operational requirements for 2 independently adjustable pulses per SPS cycle demanded an upgrading of the original system into a double pulsing system.

The availability of more modern semiconductor power switches, in this case GTO (Gate Turn-Off) thyristors, has greatly simplified the original circuit equipped with standard thyristors. These have the disadvantage that switching off can only be done with forced commutation.
However, the required trigger power and the snubber network of GTO thyristors are considerably larger than with standard thyristors.

## 2. Basic Circuit Description

### 2.1. Triangular pulse shape




Capacitor C is charged with a regulated DC power converter $U_{pc}$ to the required positive voltage via $R_l$.

At the moment, the extraction has to start, switch S is closed and a current $I_m$ starts to flow from capacitor C into the magnet ( $L_m, R_m$ ).

As is shown in annex 1 ( phase 1 ), the magnet current is a damped sinewave :

$$I_m = \frac{e^{-\delta t}}{\sqrt{1-D^2}} \cdot \frac{U_0}{Z_0} . \sin \omega t$$

with $\omega \cong \omega_0 = \sqrt{\frac{1}{LC}}$ , $Z_0 = \sqrt{\frac{L}{C}}$ , $\delta = \frac{R_m}{2L}$ and $D = \frac{R_m}{2Z_0}$

With $\omega \cong \omega_0$ the half-period time being $\cong 30ms$, the factor $e^{-\delta t}$ ( $\approx 0,94$ at t = 15ms ) has only a small influence in this application since switch S will normally be opened before the maximum of the first half-period.

Because of the polarity of the freewheel diode $D_{fr}$, no current can flow into the freewheel circuit ( $D_{fr}, R_{fr}$ ) during this phase.

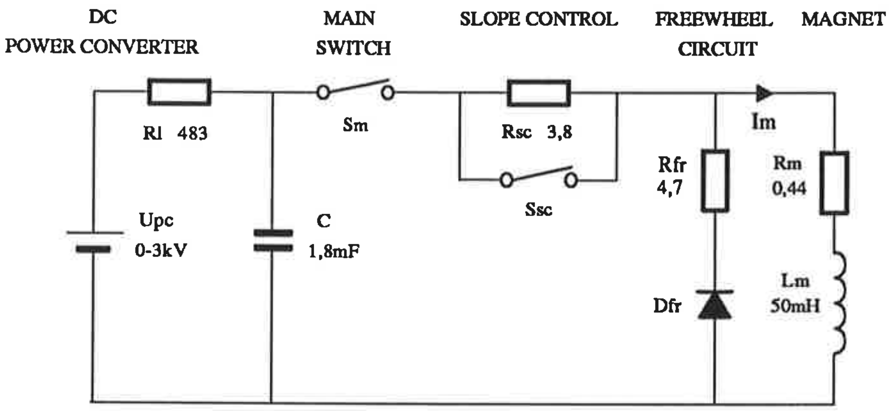
At the moment when the extraction has to stop, switch S opens and the magnet current $I_m$ is interrupted. Thereby the magnet voltage reverses and the freewheel diode $D_{fr}$ starts to conduct. In annex 1 ( phase 3 ) is shown that $I_m$ then decays with a time constant :

$$t_d = \frac{L_m}{R_f} \quad (\approx 10ms)$$

The resulting current waveform is an asymmetrical quasi-triangle.
The amplitude of its maximum can be adjusted by the capacitor voltage and the moment of its maximum by the timing of switch S.

## 2.2 Trapezoïdal pulse shape

As was mentioned in the introduction, the spill structure can be improved with a rising slope having two different gradients, the second one being approximately zero.




The required change of gradient is realized by means of a series resistor $R_{sc}$ ( nominally 3,8 Ohm ) in the main current path.

During the first part of the slope, the resistor is short-circuited with an auxiliary switch ( Slope Control ) and the gradient of the slope is determined by sin wt as was mentioned before.

At the moment the gradient has to change the Slope Control switch is opened.

In annex 1 ( phase 2 ) is shown that the current now becomes :

$$I = e^{-\delta_s.\Delta t}.\frac{U_{c(s)}}{Z}.\left\{\left(\frac{Z}{\omega_s.L}-\frac{\delta_s}{\omega_s}\right)\sin\omega_s.\Delta t+\cos\omega_s.\Delta t\right\}$$

with $\omega_s = \sqrt{\omega_0^2 - \delta_s^2}$ , $D = \frac{R_m}{2Z_0}$ , $\delta_s = \frac{R_m + R_{sc}}{2L}$ and $Z = Z_0.\left(D + \sqrt{1-D^2}.ctg\omega t_s\right)$

The fact that a generator with two independently adjustable channels is constructed allows the selection of an optimum value of $R_{sc}$ for each extraction.
As is shown in the circuit diagram of the generator ( Figure 2 ) the magnet is a symmetrical type with a grounded center connection.
This would normally also require a symmetrical generator with an output free of ground.
But for economical reasons standard unipolar dc power converters had to be used.
Therefore a circuit with a grounded dc power converter and a floating capacitor is applied. A complication of such a circuit is the fact that the capacitor then has to be charged through the lower half of the magnet, thus creating a parasitic magnet field which could create problems when one channel pulses during the charge period of the other channel.
The problem was solved by limiting the capacitor current to a neglectable value ( 3A peak ) through the resistance in the charging circuit, composed of the internal resistance of the power converter ( 150Ω ) and the charging resistor ( 333Ω ).

## 3. Circuit Simulations

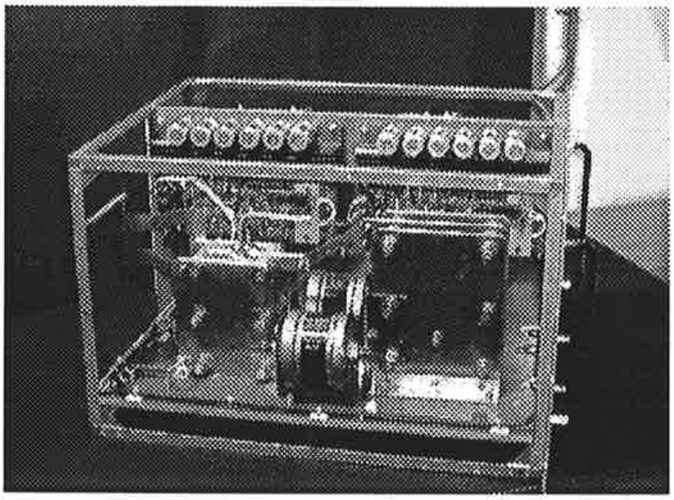
Circuit simulations for the QECD generator have been done with PSpice ™.
All plots have been made at the maximum operation voltage of 3000V.
The results, shown in Annex 2, correspond with the calculations.

Plots 1 and 2 show the natural magnet current and voltage curves ( Main and Slope Control switches closed for longer than a half-period ).

Plots 3 and 4 also show the magnet current and voltage curves but now in normal operating conditions ( main switch closed for 10ms and slope control switch closed for 7ms).

An important conclusion from plots 5 and 6 is that the Main switches will have to withstand approximately 4400 V.
This can be explained as follows : With the selected freewheel resistor the maximum negative backswing of the magnet voltage is approximately 1400V.
Therefore when both channels are operating at 3000V, the negative backswing voltage on one channel will generate a voltage of approximately 4400V over the switches of the other channel. The Slope Control switch being bypassed by a low value resistor, the Main switch must then withstand the almost entire voltage.

## 4. Switches



As was mentioned above, GTO thyristors have been selected for the Main and Slope Control switches.
The results from the circuit simulations mentioned earlier having shown that Main switch 2 has to withstand 4400V. At the moment of purchase the best available GTO devices had a rating of 4500V, which gave a too small margin. Therefore a solution with two devices in series was chosen.
The Slope Control switch unit is of the same construction as the Main switch unit but with an air cooled 3,8W resistor added to it.
The basic circuit of a Main switch unit is given in figure 1 and the photograph above shows the construction of such a unit.

As can be seen in figure1, both GTO devices have a snubber network (C1, D1, R1 and C2, D2, R2) and an antiparallel diode (D3 and D4).
In principle the selected symmetrical type of device does not need an antiparallel diode, but in practice such a diode is generally applied for improving the reverse recovery and for protection against transient voltage spikes.

At turn-off the GTO anode voltage rises rapidly. Because of their stored energy, the junction layers behave as capacitors. The current in a capacitor being $I = C\frac{dV}{dt}$, an anode voltage change will cause a current in the gate region. If this current is large enough the GTO will turn-on. A RC snubber network to limit the rate of rise of the anode voltage is therefore necessary. The network is made most effective by insertion of a diode which short circuits the resistor unidirectionally, $\frac{dV}{dt}$ is then limited by the capacitor alone.

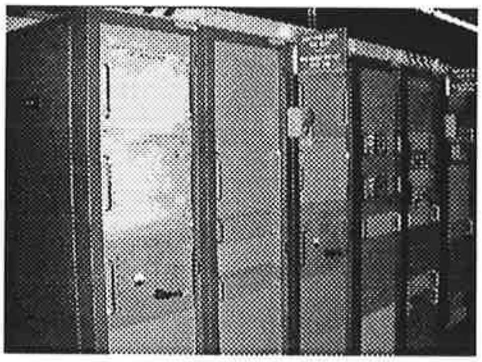
The maximum allowable $\frac{dV}{dt}$ for GTO's in this application being $500 V/_{\mu s}$ and the maximum current being approximately 600A, the minimum capacitor value is $C = \frac{600}{500} = 1,2\mu F$. The value chosen is $2\mu F$.

At turn-on the capacitor discharges through the GTO. In order to limit the discharge current to a safe value, resistor R is inserted. The value of R is calculated from the general thumb rule $RC \leq t_{on}$. For GTO's in this application $t_{on}$ being $\approx 12\mu s \rightarrow R \leq 6\Omega$. The value chosen is $5\Omega$ , limiting the current to 300A.

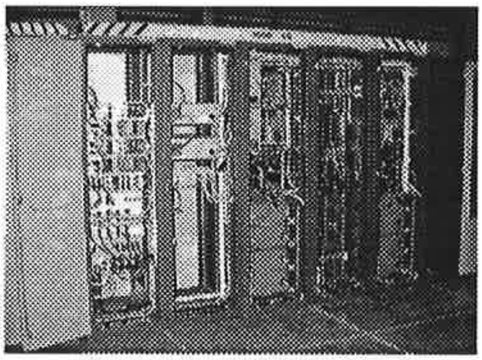
The trigger cards (GTR1 and GTR2) are standard industrial boards, purchased from GEC Plessey ™. Because of their floating operation they are powered via an isolation transformer and triggered via an optical fiber.

The photograph above shows the 2 snubber capacitors (C1 and C2) in the centre with at their left the double GTO module and at their right a module containing the antiparallel diodes, the snubber diodes and the snubber resistors. At the vertical panel behind these modules the trigger cards can be seen.

## 5. Construction



Front view



Rear view

The generator is housed in two groups of 19" electronics racks. One group of 5 racks for the power electronics ( see the above photographs ) and a second group of 3 racks for the control electronics.

The circuit diagram of the generator is shown in figure 2, the control electronics are not covered by this note.

A sparkgap, limiting the voltage across the crowbar resistor has been added for protection in case of malfunctioning.

In the original system the addition of filter circuits at the output was found to be necessary for suppression of a parasitic oscillation at the opening of the Main.
The same filters are installed in the upgraded system.

## 6. Measurement results

Measurement results are shown in figure 3. The upper plot gives the natural magnet current and voltage and the lower plot gives the magnet current in normal operating conditions.
All measurements were taken at the normal 1500V operation voltage.

## 7. Acknowledgments

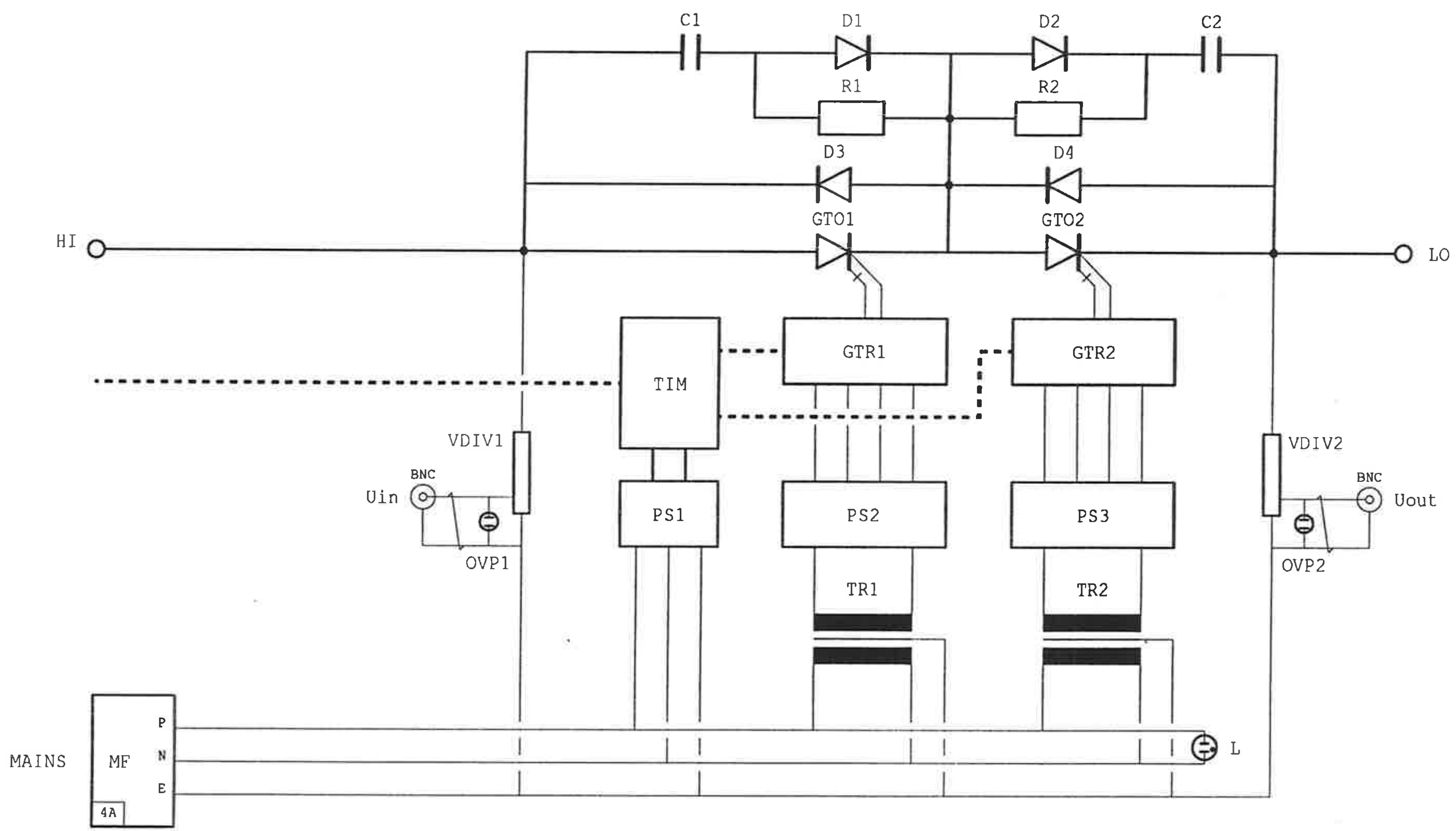
Many fruitfull discussions with Marcel Gyr, Gerhard Schröder and Gene Vossenberg were of great help to me. Etienne Carlier produced the well designed control electronics. Roland Tröhler and Jean Paul Pianfetti were responsible for the mechanics and installation. I wish to thank all of them for their cooperation and support.

**References :**

1. Half - Integer Resonant Extraction with Quasi Rectangular Spill.
   by Marcel Gyr and Eugène B. Vossenberg.

2. Generation of current pulses of quasi triangular shape with fast power thyristors
   by V. Rödel, G.H. Schröder, E.B. Vossenberg.

FIG.1 - MAIN SWITCH CIRCUIT DIAGRAM




- - - - - FIBER OPTIC LINK

LEGEND :

| | | | | | |
|---|---|---|---|---|---|
| C1,2 | - 2uF LCC PRX4500V | TIM | - Trigger Input Module | VDIV1,2 | - Voltage Divider 10M MOX2 Victoreen |
| R1,2 | - 5 Ohm GH Disc | PS1 | - Power Supply 5U15-15 Delta | OVP1,2 | - Surge Arrestor B1-C90/20 Siemens |
| D1,2,3,4 | - SM45CXC624 Westcode | PS2,3 | - Power Supply ST60A Delta | MF | - Mains Filter FN365-4/05 Schaffner |
| GTO1,2 | - 100W45R30 Westcode | TR1,2 | - Isolation Transformer Kohler | L | - Neon Lamp |
| GTR1,2 | - GDU91-20102 MEDL | | | | |

JB/CDMGQCDN

FIG.2 - CIRCUIT DIAGRAM QECD GENERATOR

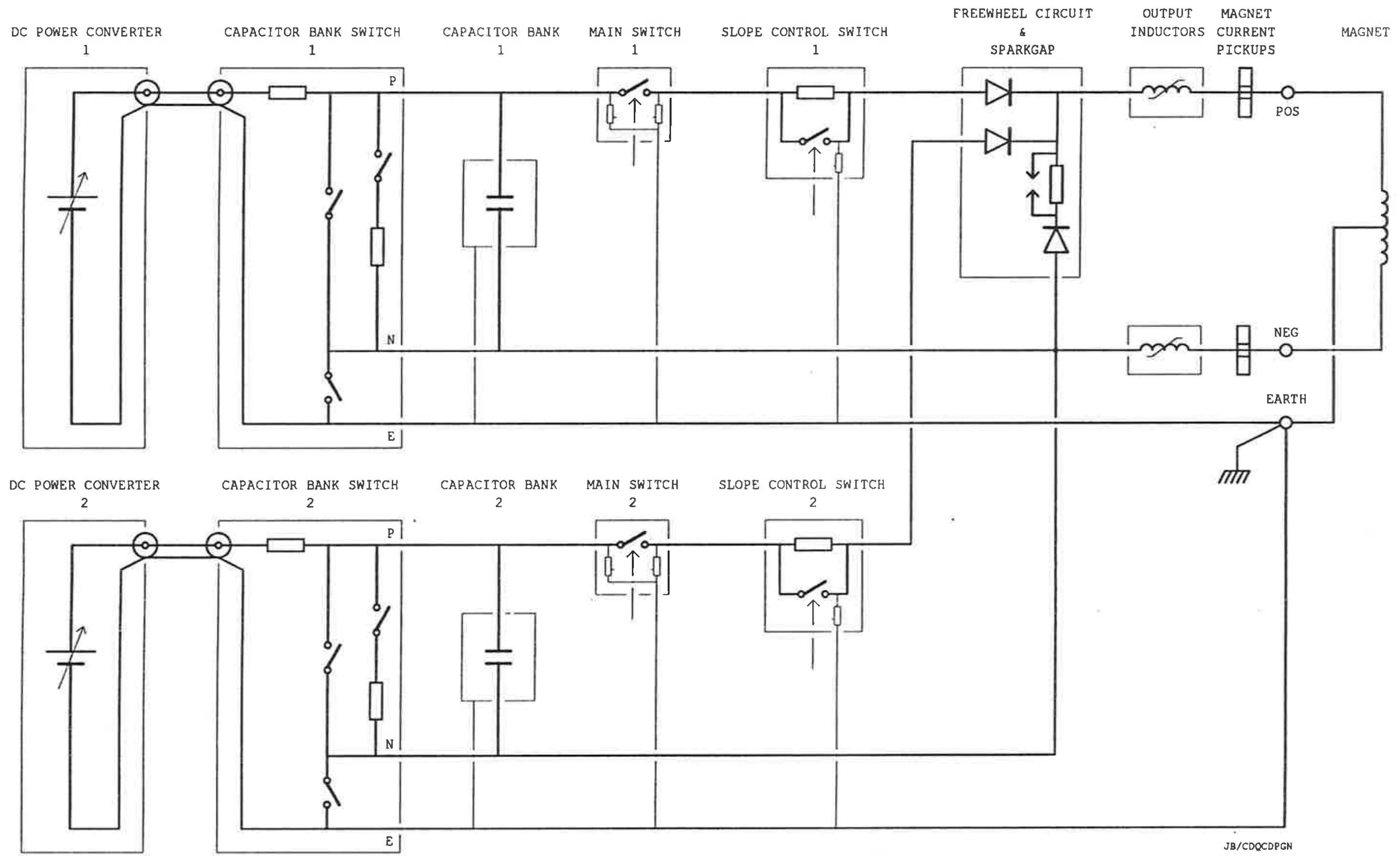
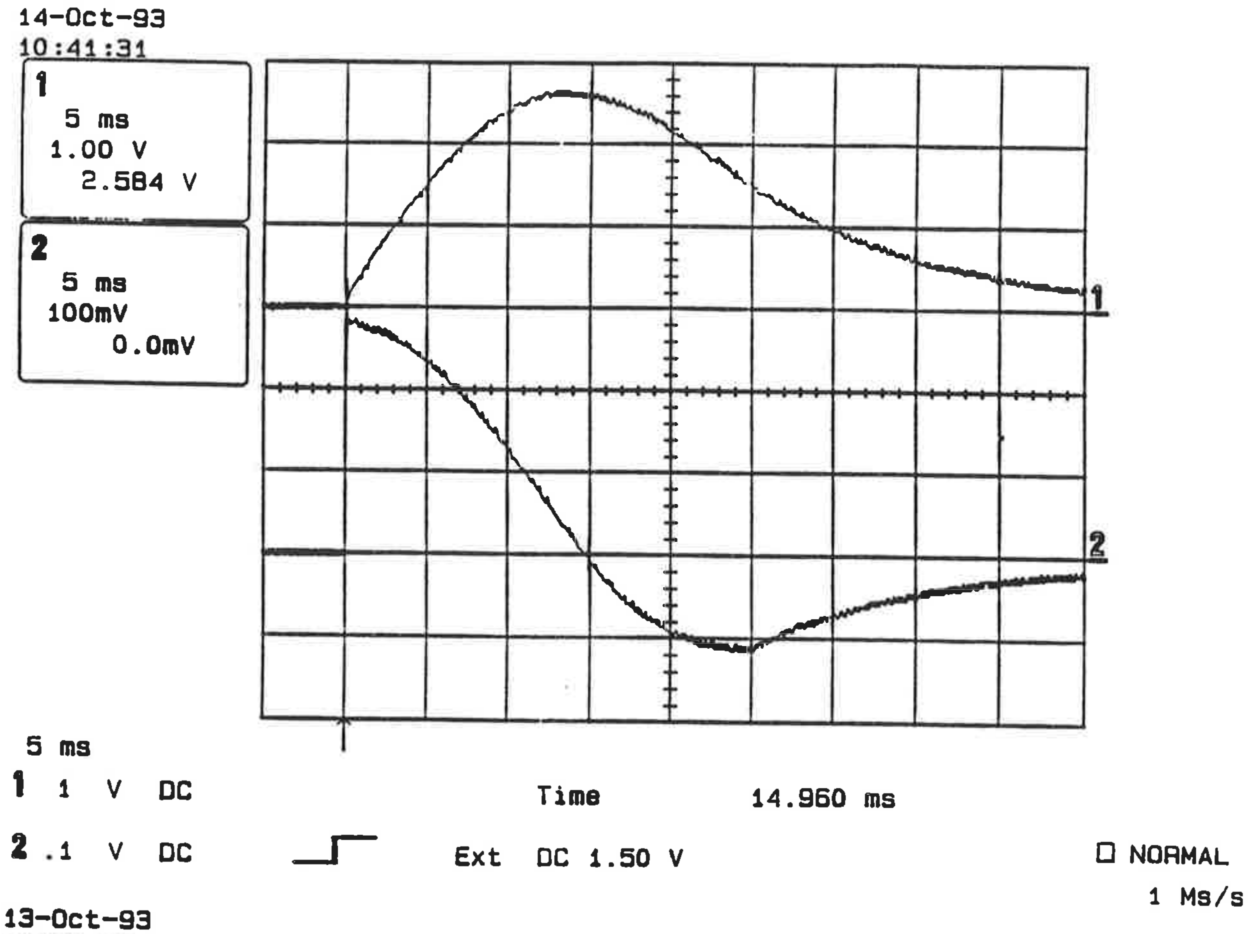
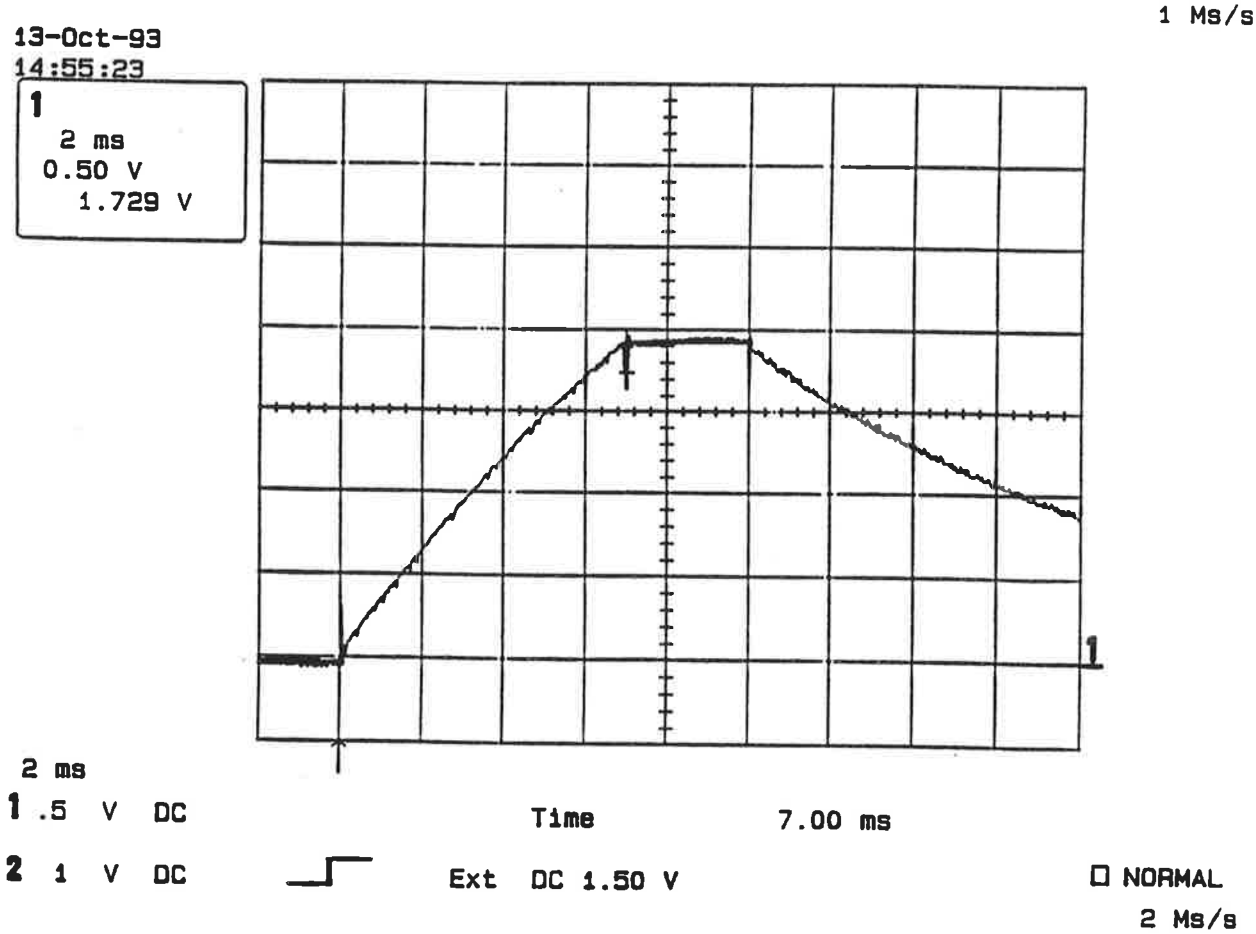


FIG.3 MEASUREMENT RESULTS

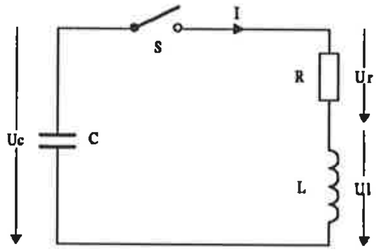


## Annex 1

# Calculations of the QECD generator circuit

**Phase 1 :**




Capacitor C is charged to voltage $U_C$ . Phase 1 starts at the moment switch S closes.

Because $U_C$ is positive, no current will flow in the freewheel circuit, which can therefore be neglected in phase 1.

With : $U_R + U_L = U_C \;;\; U_R = I.R \;;\; U_L = L.\frac{dI}{dt}$

and $I = -C.\frac{dU_c}{dt}$ (1)

The following equation can be derived : $\frac{d^2U_c}{dt^2} + \frac{R}{L}.\frac{dU_c}{dt} + \frac{1}{LC}.U_c = 0$ (2)

$U_c = A.e^{rt}$ is the general solution of this equation $\rightarrow r^2 + \frac{R}{L}.r + \frac{1}{LC} = 0$

$\rightarrow r_{1,2} = -\frac{R}{2L} \pm \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}} = -\delta \pm \sqrt{\delta^2 - \omega_0{}^2}$ with $\delta = \frac{R}{2L}$ and $\omega_0{}^2 = \frac{1}{LC}$

If $\delta^2 < \omega_0{}^2$ , which is the case for the QECD generator, both values for r are different and complex

Thus : $r_{1,2} = -\delta \pm j\omega$ with $\omega = \sqrt{\omega_0^2 - \delta^2}$

The complete solution of (2) is now : $U_c = A_1.e^{(-\delta + j\omega)t} + A_2.e^{(-\delta - j\omega)t}$

With $\frac{\omega}{\delta} = tg\varphi \rightarrow \sin\varphi = \frac{\omega}{\omega_0}$ and $\cos\varphi = \frac{\delta}{\omega_0}$

Because $e^{j\omega t} = \cos\omega t + \sin\omega t$, this equation can be written as :

$$U_c = e^{-\delta t}.(B_1\cos\omega t + B_2\sin\omega t) \quad \text{with} \quad B_1 = A_1 + A_2 \quad \text{and} \quad B_2 = j(A_1 - A_2) \qquad (3)$$

Substitution of this result into (1) gives :

$$I = C.e^{-\delta t}.\{(\delta.B_1 - \omega.B_2)\cos\omega t + (\omega.B_1 + \delta.B_2)\sin\omega t\} \qquad (4)$$

At $t = 0$ : $U_c = U_0$ and $I = 0$

Substitution into (3) and (4) gives :

$$U_0 = B_1 \text{ and } 0 = C.(\delta.B_1 - \omega.B_2) \rightarrow B_1 = U_0 \text{ and } B_2 = \frac{\delta}{\omega}.U_0 = \frac{U_0}{tg\varphi}$$

Substitution of these results into (3) gives : $U_c = \dfrac{\omega_0}{\omega}.e^{-\delta t}.U_0.\sin(\omega t + \varphi)$

Substitution into (4) gives : $I = \dfrac{1}{\omega L}.e^{-\delta t}.U_0.\sin\omega t$

The characteristic impedance of the circuit can be defined as :

$$Z_0 = \left|\frac{U_c}{I}\right| = \frac{\omega_o}{\omega}.\omega L = \sqrt{\frac{L}{C}} \quad \text{and} \quad \omega L = \sqrt{\omega_0^2 - \delta^2}.L = Z_0.\sqrt{1 - \left(\frac{R}{2Z_0}\right)^2}$$

$D = \dfrac{R}{2Z_0} = \dfrac{\delta}{\omega_0}$ is called dampingfactor $\rightarrow \dfrac{\omega}{\omega_0} = \dfrac{\omega L}{Z_0} = \sqrt{1 - D^2}$

Thus : $U_c = \dfrac{e^{-\delta t}}{\sqrt{1 - D^2}}.U_0.\sin(\omega t + \varphi)$ and $I = \dfrac{e^{-\delta t}}{\sqrt{1 - D^2}}.\dfrac{U_0}{Z_0}.\sin\omega t$

At $t = t_s$ , $Z = \dfrac{U_{c(s)}}{I_s}$ is called the dynamic impedance of the circuit .

$$Z = Z_0.\frac{\sin(\omega t_s + \varphi)}{\sin\omega t_s} = Z_0(\cos\varphi + \sin\varphi.ctg\omega t_s)$$

As was found before : $\sin\varphi = \dfrac{\omega}{\omega_0} = \sqrt{1 - D^2}$ and $\cos\varphi = \dfrac{\delta}{\omega_0} = D$

$$\rightarrow Z = Z_0.\left(D + \sqrt{1 - D^2}.ctg\omega t_s\right)$$

From the above obtained results it can be concluded that during phase 1, the magnet voltage and current are damped sinewaves with the following characteristics:

$$U_{(L-R)} = U_C = \frac{e^{-\delta t}}{\sqrt{1-D^2}}.U_0.\sin(\omega t + \varphi) \tag{5}$$

and

$$I = \frac{e^{-\delta t}}{\sqrt{1-D^2}}.\frac{U_0}{Z_0}.\sin \omega t \tag{6}$$

with $\omega = \sqrt{\omega_0^2 - \delta^2}$ , $\omega_0 = \sqrt{\frac{1}{LC}}$ , $Z_0 = \sqrt{\frac{L}{C}}$ and $\varphi = arctg\frac{\omega}{\delta}$

R being the magnet resistance $R_m$ $\rightarrow$ $\delta = \frac{R_m}{2L}$ and $D = \frac{R_m}{2Z_0}$

**Phase 2 :**

At $t = t_s$ the slope control switch is opened and thus a slope control resistor $R_s$ is introduced in the circuit. The total resistance becomes $R_t = R_m + R_s$ and thereby the values of $\omega$ and $\delta$ will change and will now become $\omega_s$ and $\delta_s$.

The time from $t_s$ onwards will be defined as $t = t_s + \Delta t$.

At $t = t_s$ : $\Delta t = 0$, $U = U_{c(s)}$ and $I = I_s$

Substitution into (3) gives : $U_{c(s)} = B_1$

Substitution into (4) gives : $I_s = C.(\delta_s.B_1 - \omega_s.B_2)$

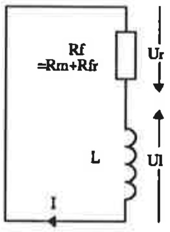
$$\rightarrow \quad B_2 = \frac{\delta_s.B_1.C - I_s}{\omega_s.C} = \left(\frac{\delta_s}{\omega_s} - \frac{1}{Z.\omega_s.C}\right).U_{c(s)}$$

Thus : $I = e^{-\delta_s.\Delta t}.\frac{U_{c(s)}}{Z}.\left\{\left(\frac{Z}{\omega_s.L} - \frac{\delta_s}{\omega_s}\right)\sin \omega_s.\Delta t + \cos \omega_s.\Delta t\right\}$

With $Z = Z_0.\left(D + \sqrt{1-D^2}.ctg\omega t_s\right)$, $\omega_s = \sqrt{\omega_0^2 - \delta_s^2}$ , $\omega_0 = \sqrt{\frac{1}{LC}}$ and $\delta_s = \frac{R_m + R_s}{2L}$

From this result it can be concluded that also during phase 2 the magnet current is a damped sinewave.

**Phase 3 :**




Phase 3 starts at the moment switch S opens. This results in a reversal of the voltage over the magnet inductance, by which the freewheel diode $D_{fr}$ starts to conduct.
The total resistance in the circuit is composed of the freewheel resistance and the magnet resistance $R_f = R_{fr} + R_m$.

For the circuit during this phase the following relations can be established :

$$U_R + U_L = 0 \;\; ; \;\; U_R = I.R_f \text{ and } U_L = L.\frac{dI}{dt} \;\rightarrow\; L.\frac{dI}{dt} + I.R_f = 0$$

The solution is : $I = e^C.e^{-\frac{R_f}{L}t}$, in which C is an integration constant.

At $t = 0$ , $I = I_0$ and therefore : $I_0 = e^C$. This results in : $I = I_0.e^{-\frac{R_f}{L}t}$

From this result can be concluded that in this phase the magnet current decays from its value at the moment the switch opened, with a time contant of $t_d = \frac{L}{R_f}$.

**Conclusion :**

A waveform, combining phase 1 and phase 3 has a rising slope determined by $\sin \omega t$ and a falling slope determined by a decay with time constant $t_d = \frac{L}{R_f}$.

In this way an asymmetrical quasi-triangular waveform can be obtained.

## Practical calculations :

Maximum voltage : $U = 3kV$

Capacitor value : $C = 1,8mF$

Magnet data : $L = 50mH$ ; $R = 440m\Omega$

$Z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{5.10^{-2}}{1,8.10^{-3}}} \cong 5,27\Omega$ , $\delta = \frac{R}{2L} = \frac{440.10^{-3}}{2.50.10^{-3}} = 4,4$ and

$\omega_0 = \frac{1}{\sqrt{L.C}} = \frac{1}{10^{-3}\sqrt{50.1,8}} \cong 105 \rightarrow \omega \cong \omega_0 = 105 \rightarrow t = \frac{2\pi}{\omega} \cong \frac{2\pi}{105} \cong 59,8ms$

$I_{MAX} = \frac{e^{-\delta t}}{\omega L}.U_0$ and $I_{MAX}$ occurring at $\frac{t}{4} \cong 15ms \rightarrow e^{-\delta t} = e^{-4,4.0,015} \cong 0,94$

Therefore $I_{MAX} = \frac{0,94}{105.50.10^{-3}}.3.10^3 \cong 537A$

The RMS current for a triangular waveform with duration t and repetition period T, is approximately :

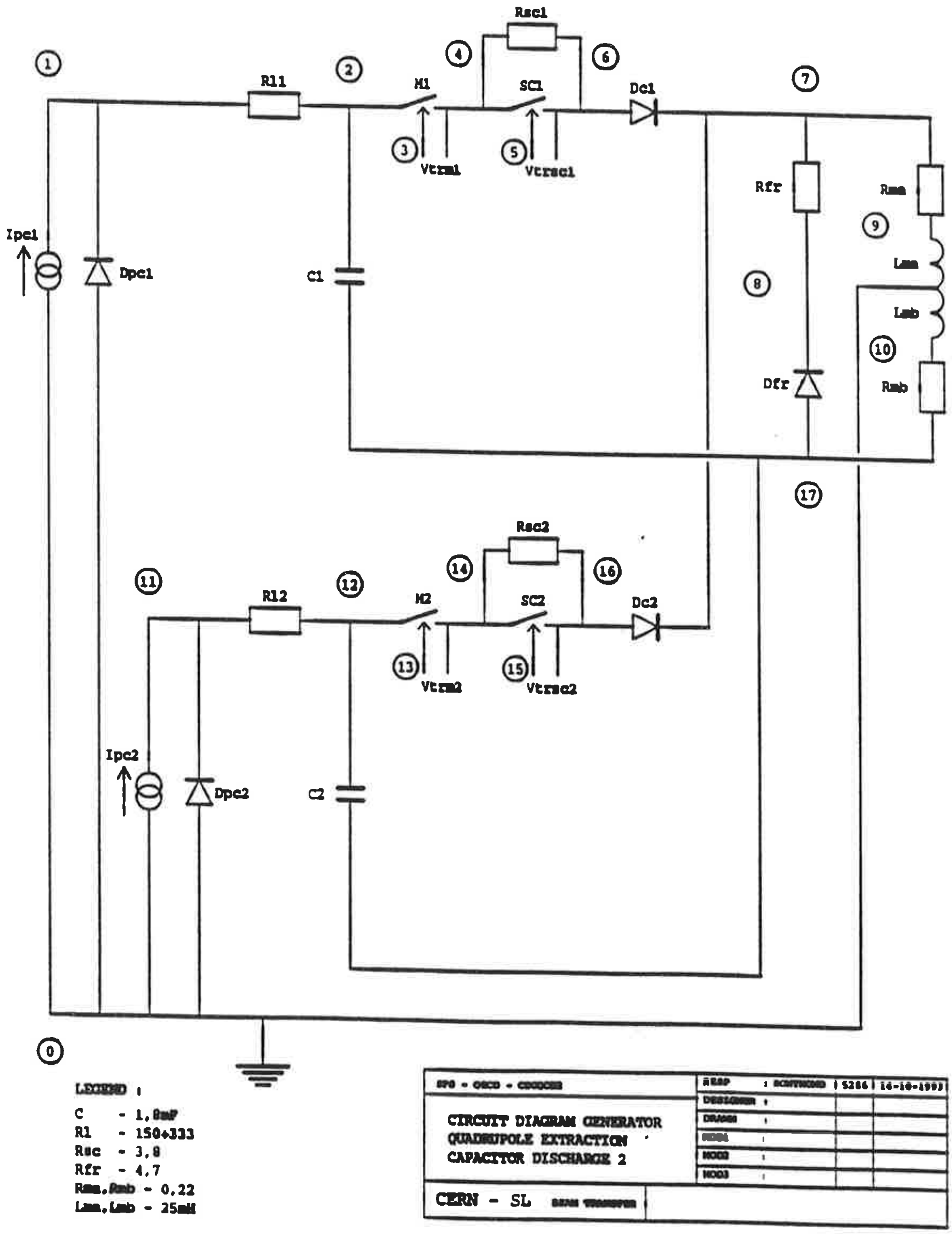
$I_{RMS} \cong I_{MAX}\sqrt{\frac{t}{3T}}$

For $t \cong 60ms$ and $T = 10s$ this gives :

$I_{RMS} = 537\sqrt{\frac{60.10^{-3}}{3.10}} \cong 24A$

## Annex 2

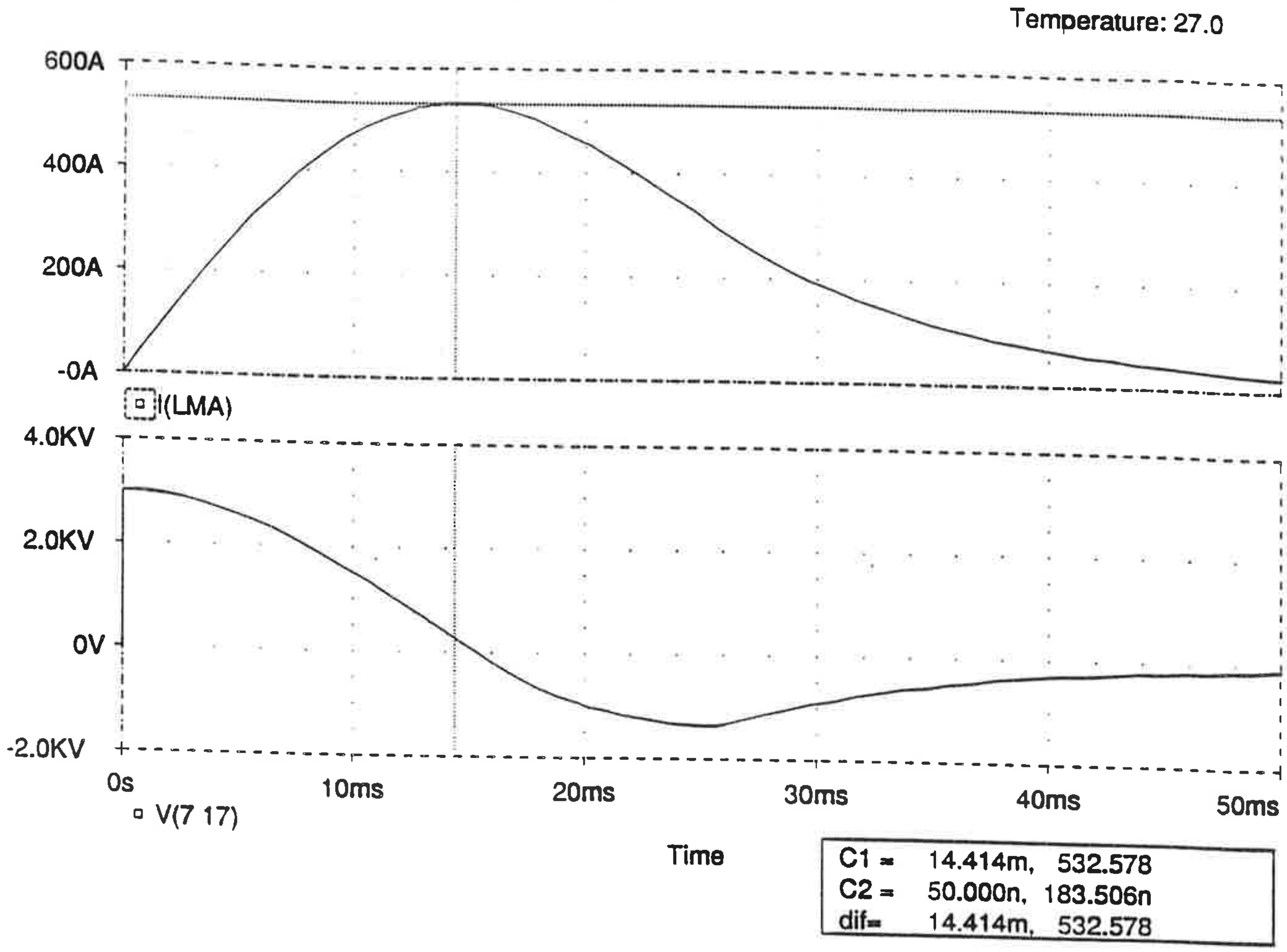
## PSpice ™ simulations :



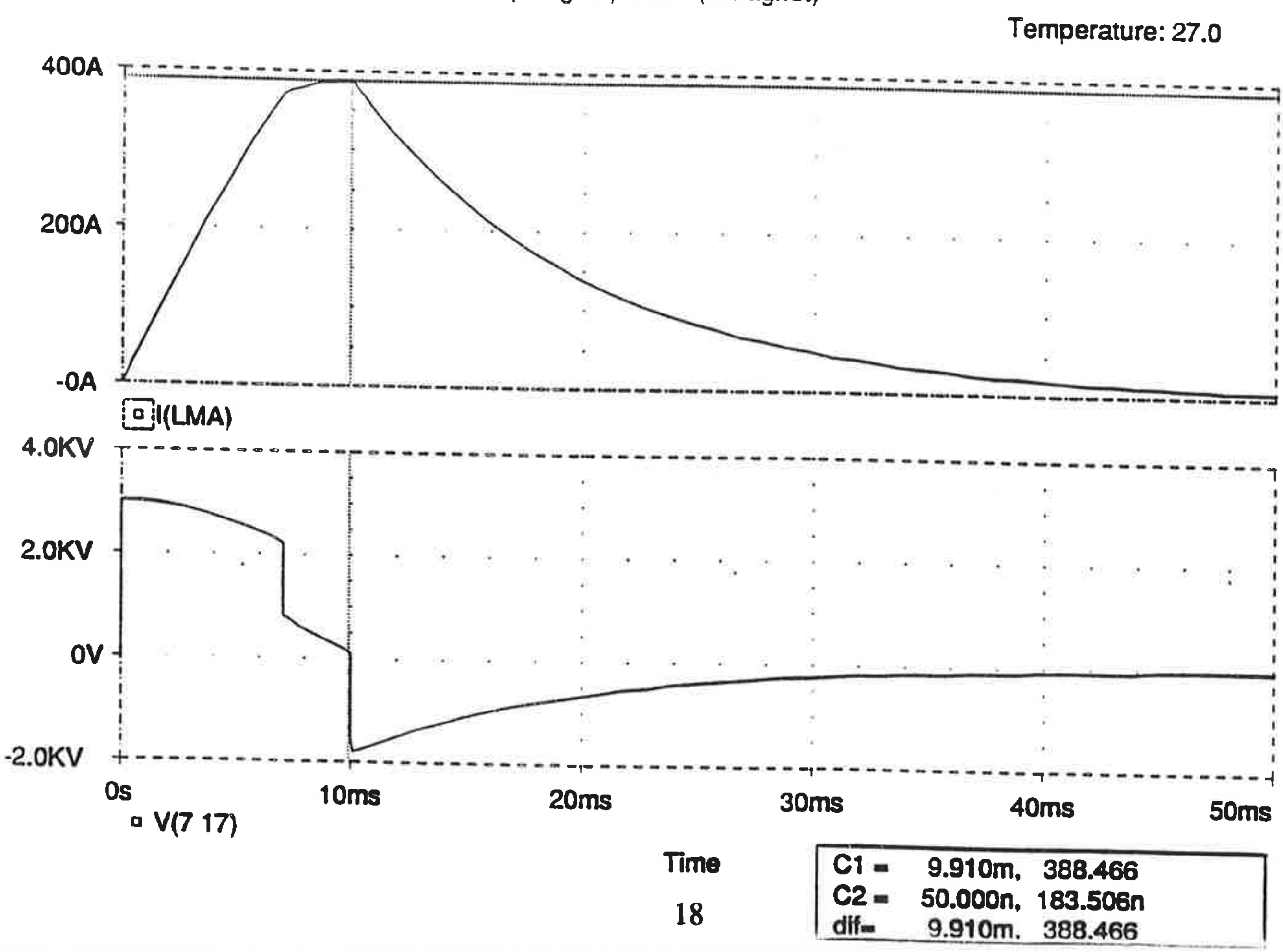
Input file - QECD2

```
IPC1      0    1         300mA
DPC1      0    1         DMODL
RL1       1    2         483
C1        2    17        1.8mF
XM1       2    3    4    SW
VTRM1          3    4    PULSE(0V 10V 0ms 5us 5us 10ms 10s)
XSC1      4    5    6    SW
VTRSC1    5    6         PULSE(0V 10V 0ms 5us 5us 7ms 10s)
RSC1      4    6         3.8

DC1       6    7         DMOD

IPC2      0    11        300mA
DPC2      0    11        DMODL
RL2       11   12        483
C2        12   17        1.8mF
XM2       12   13   14   SW
VTRM2          13   14   PULSE(0V 10V 100ms 5us 5us 10ms 10s)
XSC2      14   15   16   SW
VTRSC2    15   16        PULSE(0V 10V 100ms 5us 5us 7ms 10s)
RSC2      14   16        3.8

DC2       16   7         DMOD

RFR       7    8         4.7
DFR       17   8         DMOD
RMA       7    9         .22
LMA       9    0         25mH
LMB       0    10        25mH
RMB       10   17        .22

.SUBCKT SW     A    G    C
SGTOa     A    X    G    C    SWITCH
DPa       X    A              DMOD
CSa       A    Y              2uF
DSa       Y    X              DMOD
RSa       Y    X              5
SGTOb     X    C    G    C    SWITCH
DPb       C    X              DMOD
DSb       X    Z              DMOD
RSb       X    Z              5
CSb       Z    C              2uF
.ENDS

.MODEL DMOD       D
.MODEL DMODL D(BV=3000V)
.MODEL SWITCH VSWITCH(RON=5E-3 ROFF=1E+6 VON=10 VOFF=0)
.IC V(2)=3000V
.IC V(12)=3000V
.TRAN .001ms 50ms UIC
.OPTIONS RELTOL=.001
.OPTIONS VNTOL=.1
.OPTIONS ABSTOL=.1
.OPTIONS ITL4=10
.PROBE
.END
```

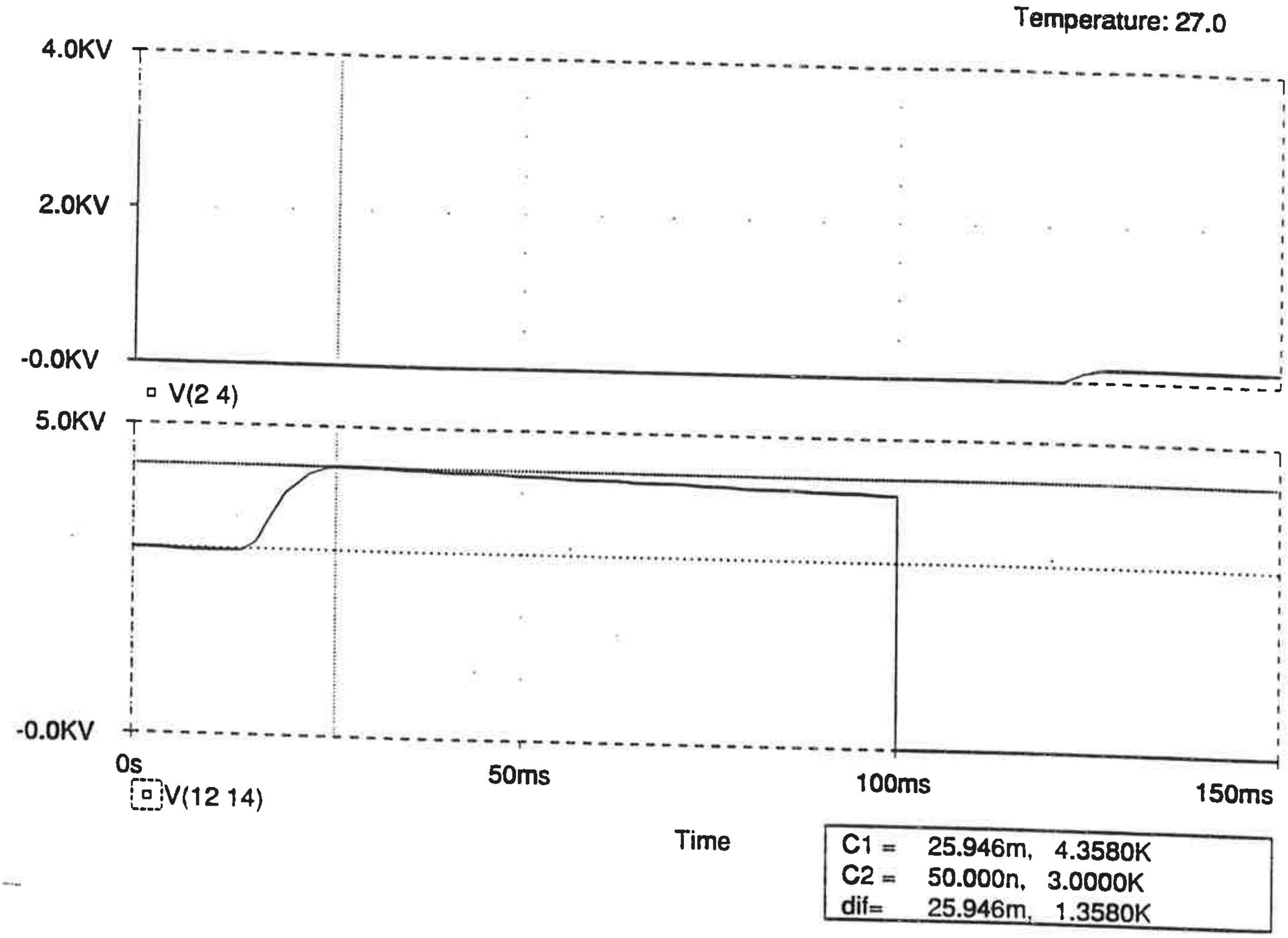
PSPICE PLOTS 1 (Imagnet) and 2 (Umagnet)




PSPICE PLOTS 3 (Imagnet) and 4 (Umagnet)



PSPICE PLOTS 5 (Umain 1) and 6 (Umain 2)



Distribution :

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