HIGH CURRENT WITH HIGH PRECISION FLAT-TOP CAPACITOR DISCHARGE POWER CONVERTERS FOR PULSED SEPTUM MAGNETS

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ABSTRACT

In the field of the accelerator, capacitor discharge power converters are widely used.

The requirements of the capacitor discharge power converters imposed by the operation of the accelerators, especially for the pulsed septum magnets, demand particular technical solutions.

The operational aspects around the proton synchrotron -PS- at CERN are reviewed.

The main features of the capacitor discharge power converters for the pulsed septum magnets are described with emphasis on:

-the high current 30kA;

-the duration of the flat-top, with high precision 10E-4;

-thermal and magnetic problems owing to the irregular pulses, current and timing modulation;

-the addition of third harmonic components for the discharge pulse;

-the insertion of an active filter;

-the general regulation and electronic crate.

Recently, to control these converters, a new electronic (with the G64 bus) has been developped. The continuous evolution allows to plan the manufacture of the power converters for the new pulsed septum magnets in the transfer line Booster (PSB) - PS, taking into consideration the future requirements for the LHC, with better standardization and reliability.

1- GENERAL DESCRIPTION

The accelerators use a large quantity of capacitor discharge power converters, particularly in the injection and transfer line to extract and to guide the beam. The principle of these power converters is based on discharge of the capacitors in synchronization with the beam.

Most of the capacitors discharge power converters are designed from a resonant discharge circuit, with the possibility of energy recuperation (through the magnet or an auxiliary inductance) or energy destruction (through auxiliary inductances and resistances). The energy destruction circuit is used when pulse to pulse peak magnet current modulation is required (the voltage after energy recuperation could be higher than the next pulse expected).

Depending on the magnet and the operation, the capacitor discharge power converters for pulsed septum magnet are designed to obtain a precision of 10E-4 during 200µsec to 600µsec with a current of 30 kA maximum.

2- PULSED SEPTUM MAGNETS AROUND THE PS

The septum magnets [1] require a high current, during the ejection for the extraction of the beam. The table 1 shows the current, the resistance and the inductance of the magnets.

Table 1

MAGNET	I max (A)	L(uH)	R(mOhm)
PR.SMH16	30000	5.53	0.50
PR.SMH26	8000	1.03	0.80
PR.SMH58	24000	2.56	0.24
PR.SMH74	14000	2.00	0.34
PR.SMH92	14000	2.00	0.34
HR.SMH00	20000	2.00	0.34
BI1.SMV	20000	0.30	0.03
BI2.SMV	20000	0.30	0.03
BI4.SMV	20000	0.30	0.03
BI.SMH	3500	6.00	1.50
BTSMV30	2000	5.90	0.20
BT1.SMV10*	30000	2.14	0.11
BT4.SMV10*	30000	2.14	0.11
BT.SMV20*	30000	2.14	0.11
BE.SMH*	6000	20.00	3.32
PI.SMH42*	35000	1.23	0.07

∗ future manufacture

The deflection of the beam is given by the formula :

$$\alpha = \frac{300 \cdot B \cdot l}{p}$$

α : deflection (milliradians)

l : equivalent length (meters)

B : magnetic field (Tesla)

p : Beam momentum (Gev/c)

For example, the deflection of the beam with the septum 16 is 30 milliradians with 1 Tesla of magnetic field and equivalent magnetic magnetic lenght of 2 meters.

The situation of the pulsed septum magnets around the PS and the PSB is shown Fig. 1.

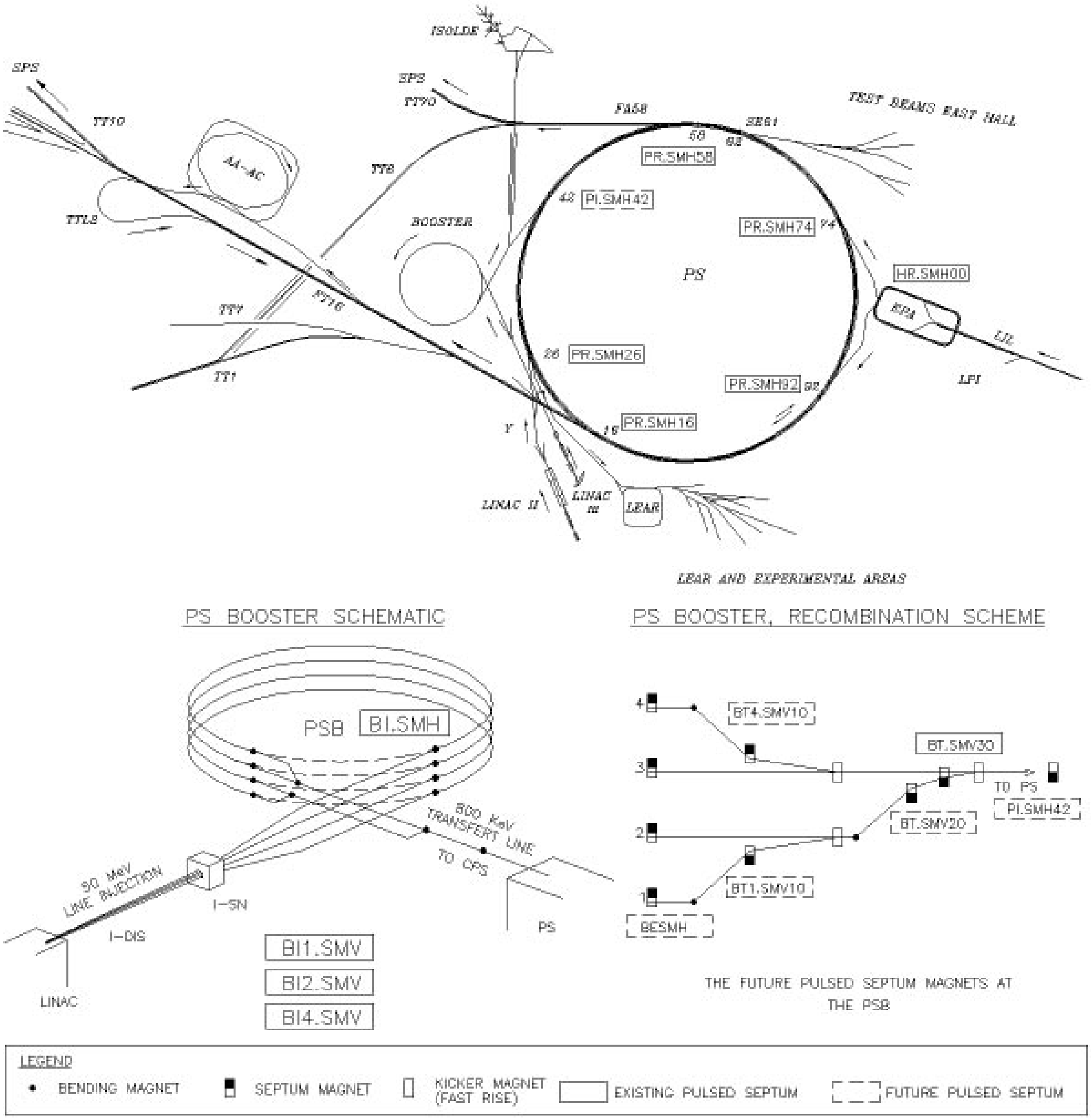


Fig. 1 : the pulsed septum magnets around the PS and the PSB.

3- OPERATIONAL ASPECTS [2]

Particle beams of different kinds and characteristics are exchanged between the PS and the other accelators or external beam transport lines as shown table 2 .

Table 2

ACCELERATORS OR BEAM LINES	PARTICULES
Linac 2	p
Linac 3	ions Pb
PSB	p , ions Pb
AAC, LEAR	p , p bars
LIL, EPA	e+ , e-
PS	p,p bars,e+,e-,ions Pb
TT70 eject. SPS-LEP	e-,p bars
TT10eject. AAC et SPS-LEP	p ,p bars,e+ ,ions Pb

The PS supercycle is made of the basic cycles A,B,C,D,E,F,G,H dependent on the use of the different beams.The Fig. 2 shows the basic PS cycles.

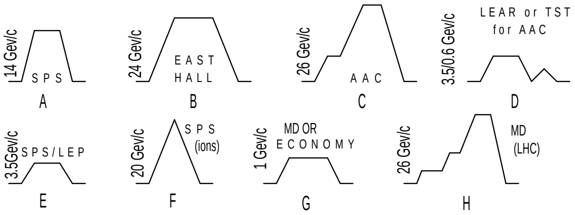


Fig. 2 : Basic PS cycles.

During operation with leptons at 3.5 Gev/c the double batch mode requires a stable current flat-top and double pulses at 30 msec interval.

Because of the irregular pulse repetition and the pulse to pulse modulation, the power supply of the septum 16 is the most demanding [3]. An example of PS supercycle is shown in Fig. 3.

The working instants of the septum 16 power converters are symbolised by the markers below.

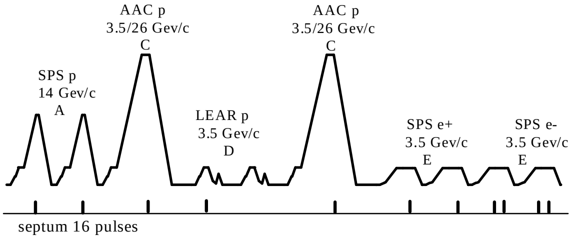


Fig. 3 : example of PS supercycle

The pulsed capacitor discharge power converters for the septum 16 must work during the ejection at the values indicated in table 3.

Table 3

Line PLS	Beam	I septum
FE16S-FE16A	protons 26 Gev/c	28700 A
FE 16I	ions 20 Gev/c	21800 A
CT	protons 14 Gev/c	14400 A
FE 16L	positrons 3,5 Gev/c	3400 A
FI 16A	p bars 3,5 Gev/c	3790 A

4- PRINCIPLE OF THE PULSE CAPACITORS DISCHARGE POWER CONVERTERS.

The principle is based on the charge and discharge capacitors through a resonant circuit between capacitors and the load.

The charging current of the capacitors is controlled via thyristors on the primary side of a high voltage transformer. The d.c. voltage required at the capacitor terminals comes from the rectifier on the secondary side of the transformer.

The d.c. voltage and current are measured by voltage dividers and a shunt.

Once charged, the capacitors are discharged via a power thyristor through a third harmonic circuit and a choke for the active filter. The discharge is adapted with a matching transformer to obtain high current. A power diode is connected in series with a choke and a resistor to destroy the energy in order to obtain the pulse to pulse modulation facilities.

The scheme of the power converter is shown Fig. 4.

5- THE THIRD HARMONIC CIRCUIT

The classical equation of the discharge current in a resonant circuit (with p Laplacian) is:

$$I(p) = \frac{U}{L} \cdot \frac{1}{p^2 + 2 \cdot \xi \cdot \omega_0 \cdot p + \omega_0^2} \quad [\mathrm{A}]$$

with $\xi << 1$ the time domain equation is:

$$i(t) = \frac{U}{L \cdot \omega} \cdot e^{-\xi \omega_0 \cdot t} \cdot \sin \omega t$$

$$\omega_0 = \frac{1}{\sqrt{L \cdot C}} \qquad \omega = \sqrt{\frac{1}{L \cdot C} - \frac{R^2}{4 \cdot L^2}} \qquad \xi = \frac{R}{2} \sqrt{\frac{C}{L}}$$

In order to obtain a better flat-top current than the basic sinusoidal discharge current, a third harmonic with extra parallel or series L, C circuit is added.

The two possibilities of the third harmonic

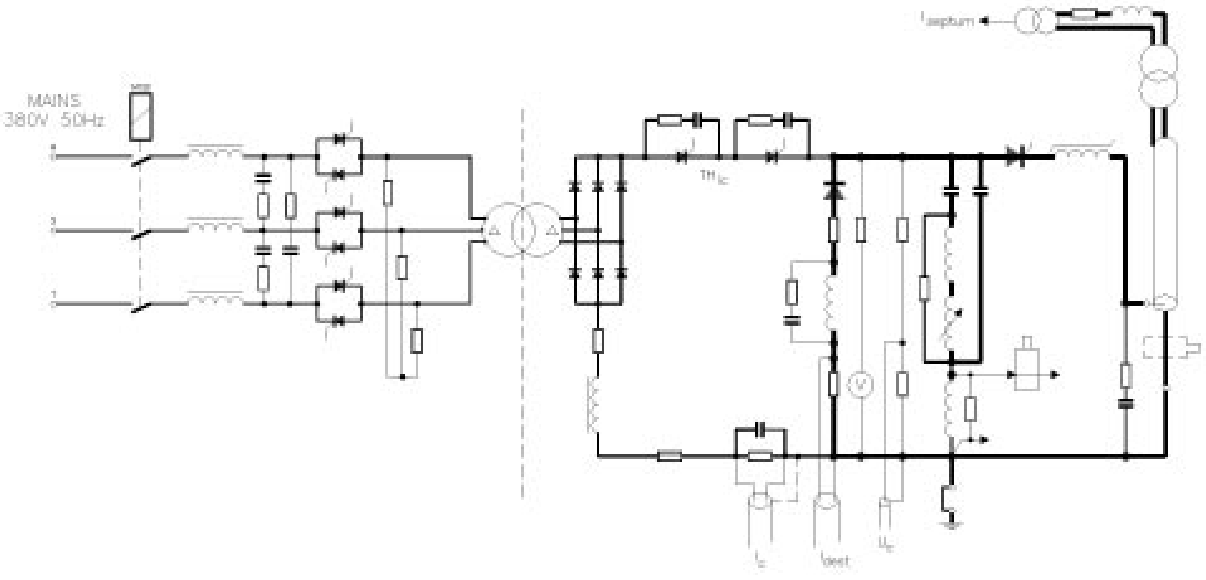
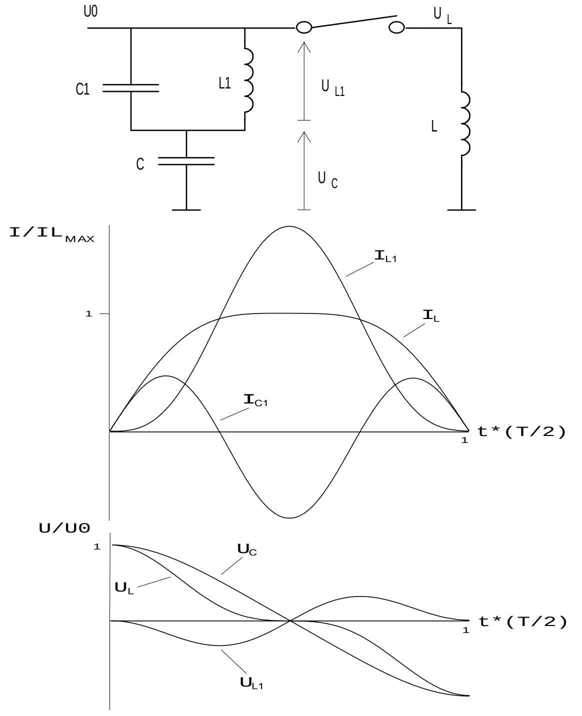


Fig. 4 : scheme of the power converter

are shown Fig. 5. With the ideal lossless case, the basic formula is :

$$i(t) = k_1 \cdot \sin\omega t + k_2 \cdot \sin 3\omega t$$

a) third harmonic circuit with serial capacitors



b) third harmonic with parallel capacitors

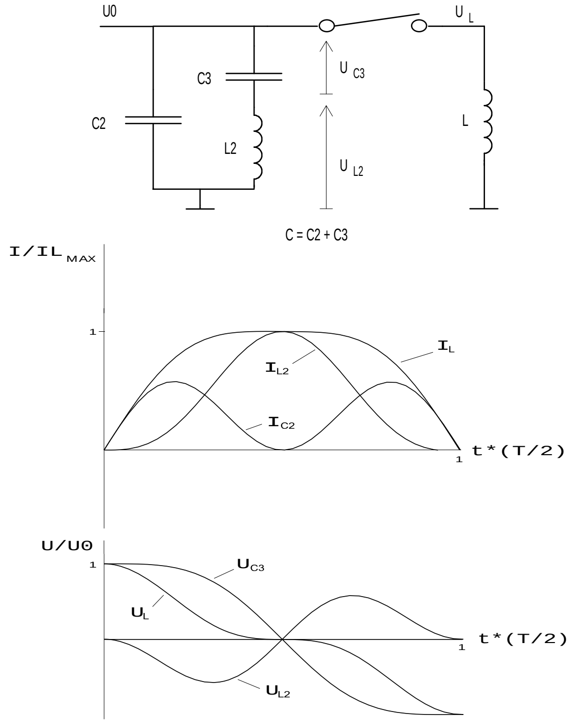


Fig. 5 : electrical circuit and waveforms of the two possibilities of the third harmonic.

To optimize the third harmonic, it is necessary to adjust the L, C circuit. An example of simulation for the design of the power converter SMH42 is also shown Fig. 6.

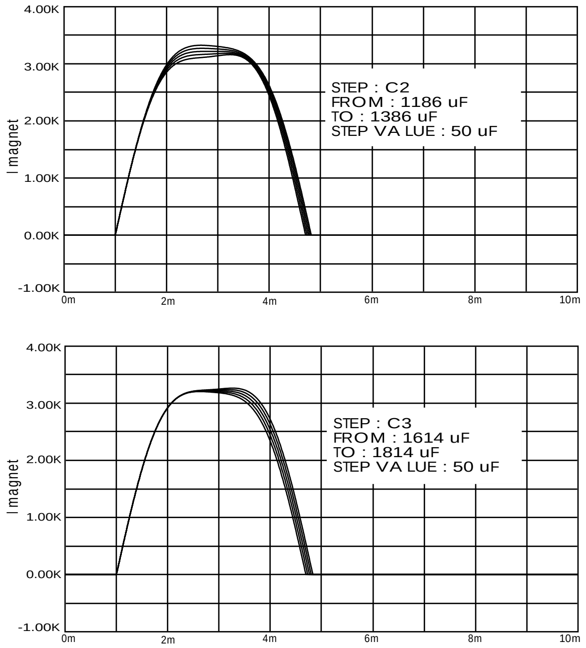


Fig. 6 : waveforms with third harmonic components (ex. : SMH42) and simulation to adjust the flat top.

Fig. 7 shows the difference between the top of the magnet current with third harmonic and without third harmonic. In Fig. 7, the flat top adjustment possibilities with L variations are shown.

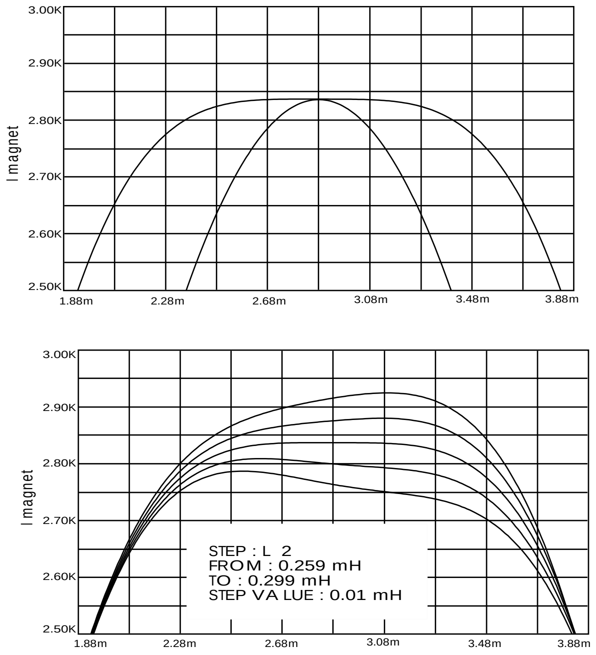


Fig. 7 : comparaison and adjustement of the third harmonic with the vertical injection booster pulsed septum power supply.

These examples are from the power supply of the vertical injection booster pulsed septum magnets.

6- MAGNETIC AND THERMAL PROBLEMS IN RELATION TO TIMING AND AMPLITUDE MODULATION.

The current reproducibility and precision $\Delta I / I$ for the septum magnet is 100 ppm during the flat -top (200 to 600 μsec).

Any minor variations lead to the non-respect of this stability.

The variation of the temperature and magnetic problems caused by irregular repetition rate must be compensated to obtain the right stability.

6-1 **The thermal problem** : At high current, with the same repetition rate and the same voltage on the capacitors, the variations are shown on the Fig. 8.

All the variations caused by the temperature are seen by the converter with the square of the ratio of the matching transformer.

$$R = R_1 + m^2 \cdot R_2$$

$$L = L_1 + m^2 \cdot L_2$$

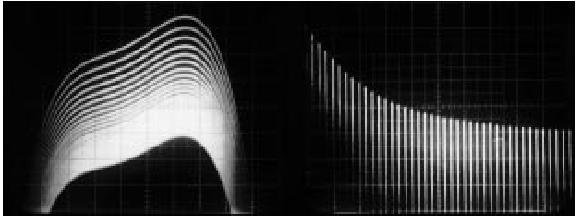
R, L resonant circuit ;

R_1, L_1 primary circuit ;

R_2, L_2 secondary circuit ;

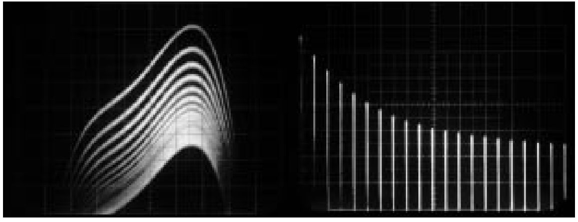
m ratio of the matching (4< m <50) ;

Tr = 1,2 s Im = 27 kA m = 12



Im : 30 A/d ; 100 uS/d Im : 30 A/d ; 5 s/d

Tr = 2,4 s Im = 27 kA m = 12



Im : 15 A/d ; 100 uS/d Im : 15 A/d ; 5 s/d

Fig. 8 : current variations with the same voltage on the capacitors and repetition rate.

The studies of the variation, with regular and irregular repetition rate are indicated in Figs. 9 and 10.

a) Regular repetition rate with the same value of current:

Two curves of instantaneous temperature for repetition times of 1.2 second and 2.4 seconds are shown schematically in Fig. 9.

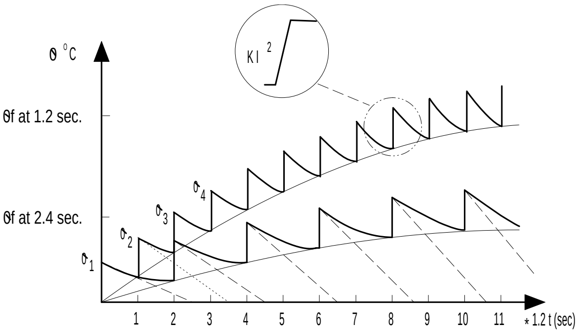


Fig. 9 : curve of increase of temperature with 1.2 sec. and 2.4 sec of repetition time.

The mathematical expressions of these curves are:

$$\theta_1 = kI^2$$

$$\theta_2 = kI^2 \cdot e^{-t/\tau} + kI^2$$

$$\theta_3 = (kI^2 \cdot e^{-t/\tau} + kI^2)e^{-t/\tau} + kI^2$$

$$\theta_4 = ((kI^2 \cdot e^{-t/\tau} + kI^2)e^{-t/\tau} + kI^2)e^{-t/\tau} + kI^2$$

$$\theta_n = kI^2(e^{-t/\tau} + e^{-2t/\tau} + \ldots\ldots e^{-nt/\tau}) + kI^2$$

$$\theta_f = kI^2 \cdot \sum_{n=1}^{n=\infty} (e^{-t/\tau})^n$$

b)Irregular repetition rate with amplitude modulation of the current:

An example of an increasing temperature curve is shown schematically in Fig. 10.

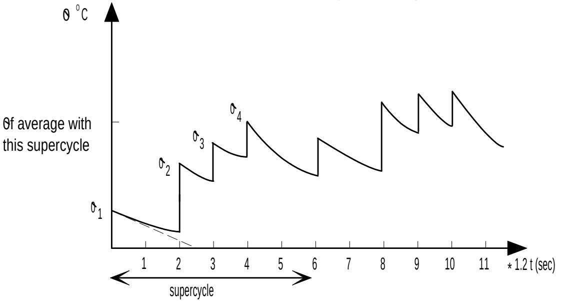


Fig. 10 : curve of increase of temperature during a supercycle.

The mathematical expressions of these curves are:

$$\theta_1 = kI_1^2$$

$$\theta_2 = kI_1^2 \cdot e^{-t1/\tau} + kI_2^2$$

$$\theta_3 = (kI_1^2 \cdot e^{-t1/\tau} + kI_2^2)e^{-t2/\tau} + kI_3^2$$

$$\theta_4 = ((kI_1^2 \cdot e^{-t1/\tau} + kI_2^2)e^{-t2/\tau} + kI_3^2)e^{-t3/\tau} + kI_4^2$$

$$\theta_n = kI_1^2 \cdot e^{-\frac{t1+t2+..t(n-1)}{\tau}} +....+kI_{n-1}^2 \cdot e^{-\frac{t(n-1)}{\tau}} + kI_n^2$$

$$\theta_f = k\sum_{1}^{n-1} I_n^2 \cdot e^{-\sum_{n}^{n-1} tn/\tau}$$

We can demonstrate that $\Delta I \approx kI_{\theta_f} \cdot \theta_f$.

So, with a regular rate (t = regular rate) and the same current:

$$\theta_f = kI^2 \sum_{n=1}^{n=\infty} (e^{-t/\tau})^n$$

$$\Delta I = k'I^3 \sum_{n=1}^{n=\infty} (e^{-t/\tau})^n$$

With irregular rates and amplitude varying current :

$$\Delta I = k''I_n \sum_{1}^{n-1} I_n^2 \cdot e^{-\sum_{n}^{n-1} tn/\tau}$$

ΔI is the current correction to obtain a current stability independent of the temperature. To correct this variation, the regulation must increase or decrease the voltage on the capacitors, before the discharge.

6-2 Magnetic variations: The matching transformer is a special manufacture with a very low stray inductance (0.3µH referred to the secondary).

To reduce the stress on the septum magnet and to obtain pulse-to-pulse modulation, the negative pulse is supressed. However in this case, with amplitude modulation, the remanent induction is not stable, the level depends on the current value and the precision of the discharge current is influenced. In order to minimize the variations, an air gap is used in the magnetic circuit.

7- THE ACTIVE FILTER FOR FLAT-TOP CURRENT.

To obtain the flat-top current with a stability of 10^{-4} and a time of 300 µsec (600 µsec. for the ions) an active filter is necessary.

The principle of the active filter is indicated in Fig. 12. The voltage at the main capacitors is regulated to give a current slightly higher than the reference current. As $Z_1 \rangle\rangle Z_2$ the current of the active filter is $\approx$200A for a flat top of 300 µsec depending on the circuit values.

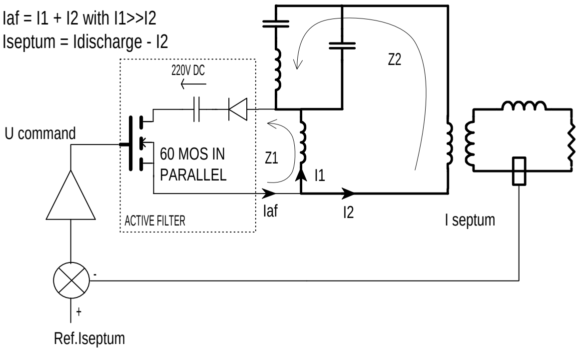


Fig. 12 : principle of the active filter

With $Z_1 \rangle\rangle Z_2$ we can pull the excess current through the inductance of the active filter. The system acts in closed loop through the matching transformer, the current transformer and the active filter composed of 60 MOS (type BUZ 45) in parallel.

Fig. 13 shows the Bode plot of the gain of the ratio I septum / I active filter and the magnet current step response for U command = 1 V in open loop.

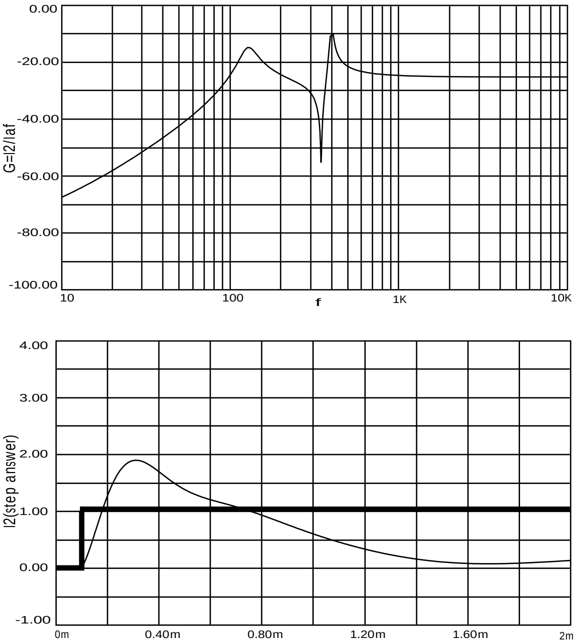


Fig. 13 : Bode plot between I2 and I active filter and transient response of the system in open loop without correction.

We can consider the active filter as a current source in opposite direction to the current from the discharge of the main capacitors. The block diagram of the control system is shown in Fig. 14.

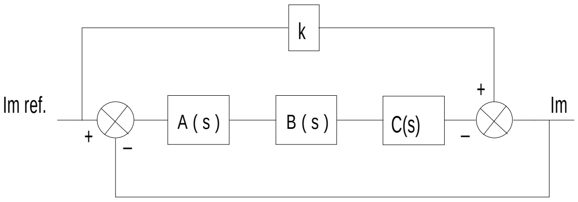


Fig. 14 : block diagram of active filter regulation

Thus the system is composed of:

- a controller : PD or PID as below (PR.SMH16 values) :

$$A(s) = \frac{k \cdot (1 + 11e - 6 \cdot s) \cdot (1 + .1e - 3 \cdot s)}{(1 + 1e - 6 \cdot s) \cdot s}$$

- a block representing the power MOS transfer function :

$$B(s) = \frac{30 \cdot (1 + 2.3e - 5 \cdot s)}{4.75e - 9 \cdot s^2 + 66.9e - 6 \cdot s + 1}$$

- a block representing the power circuit :

$$C(s) = \frac{I2}{Iaf} = \frac{A \cdot s^4 + B \cdot s^3 + C \cdot s^2 + D \cdot s}{a \cdot s^4 + b \cdot s^3 + c \cdot s^2 + d \cdot s + 1}$$

- a parameter K that represents the main capacitor discharge.

This model allows the study of the accuracy and stability of the system. Fig. 15 indicates a result from simulation with PID controller at 15000A and Fig.16 the real curves with different current values. The simulations are realised with MC4.

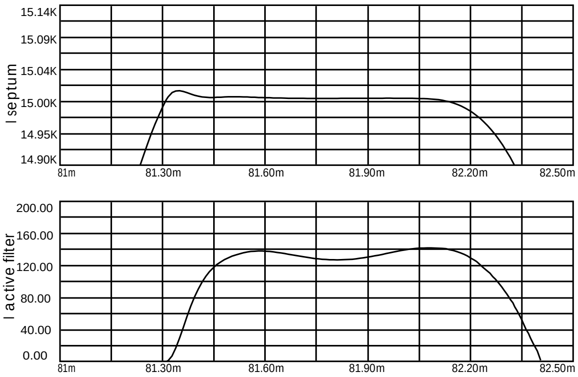
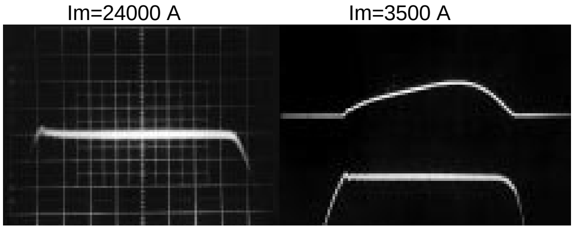


Fig. 15 : results of a simulation with PID controller and PR.SMH16 system values.



Im : 30 A/div. 100uS/div Im : 30 A/div. Iaf : 50 A/div.

Fig. 16 : septum current (PR.SMH16)

8- GENERAL REGULATION AND ELECTRONIC CRATE

The general diagram of the regulation circuits is shown Fig. 17.

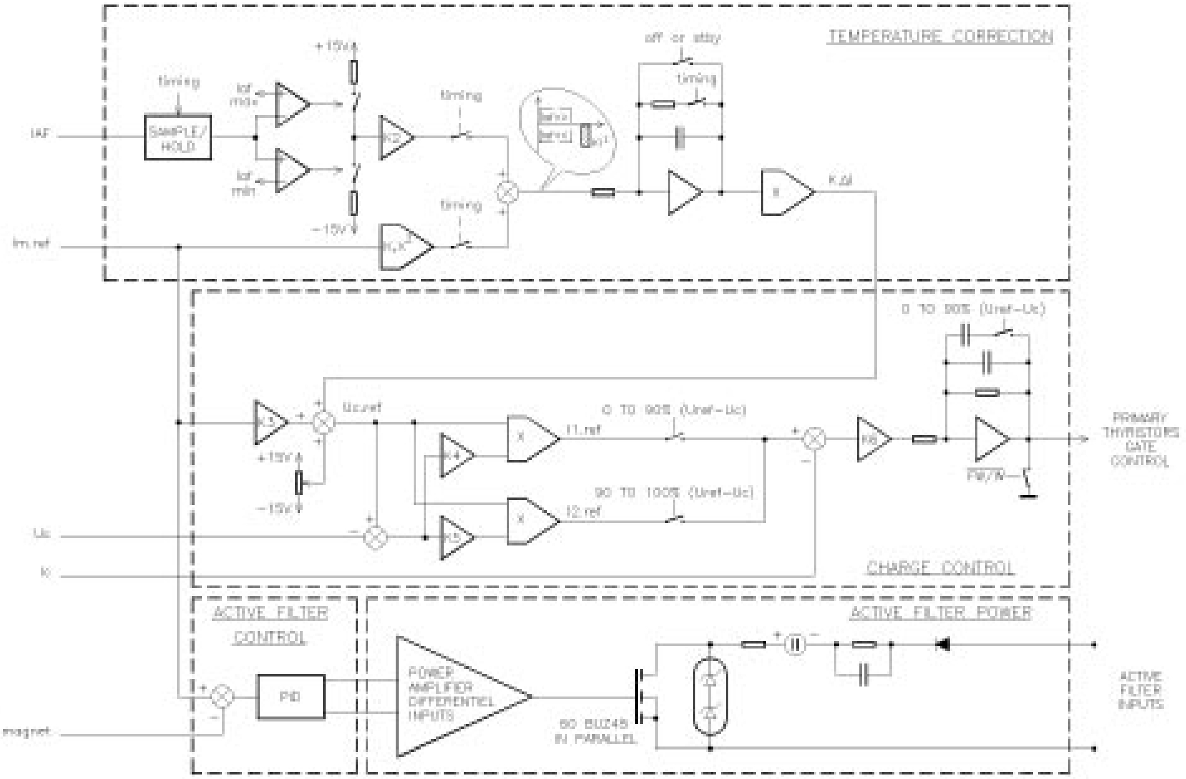


Fig. 17 : general diagram of the regulation systems.

To optimize the results, the complete regulation requires the following circuits:

-regulation of charge capacitors: voltage regulation with charging current loop.

-correction for amplitude and timing modulation: simulation of temperature.

-circuit regulation for active filter control

-active filter power.

To compense the different time constants and the long term effects, the active filter current is verified at each discharge and a correction is given if the current is too low or too high, so we obtain permanently the right value for the the compensation of the temperature curve.

Electronic crate:

The electronic crate uses a G64 bus with a 6809 Motorola microprocessor.

The electronic cards have been developed to respect different criteria : standardization, maintenance, protocol, timing with sequence forewarning, warning , start, measure pulses. The cards used inside a crate for these pulsed power supplies are given in the table 4.

Table 4

2 × 32 Europe		G64 bus
Gate control "Argentine"		Micro term interface
Capacitor discharge control		PIA opto
Active filter control		2 PIA
PIA interface		Fast ADC 16 bits
Analog default		6809 CPU RAM/ROM
Thermal correction		Surveyor simulation timing
Timing unit		Single transceiver or 1553
Relay unit 1 and 2		DAC 16 or 14 bits
HOLEC DCCT		

All the electronic is inside this crate as well as the interface for the control, with MIL1553 or Europe Single Transceiver.

This crate is controlled locally by a touch-panel and a display.

9-CONCLUSION

The enormous work realized on this type of power converters have permitted to achieve the extremely demanding performances required for the ejection of different particles at different energies.

In spite of the complexity of these power converters - different characteristics of the magnets, special operation - **we have treated all the power converters with the same approach which leads to a better standardization and reliability.**

The experience in this field allows us to look at the future with optimism about the replacement of the d.c. septa of the transfer line PSB-PS by pulsed septa. **Consequently, we foresee the manufacture of capacitor discharge power converters, well able to take into account the future requirements (PSB to 1,4 Gev) for the Large Hadron Collider (LHC).**

ACKNOWLEDGEMENTS

I would like to thank the numerous people who have worked on the capacitor discharge pulsed power converters, as well as those who were in charge of studies and the tests.

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