EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
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Departmental Report

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The BTF (Beam Transfer Facility) DC/Pulsed 50 kW Power Supply for DAΦNE injector

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CERN has designed and built a special power supply for the INFN National laboratory of Frascati. This power supply is used to deflect the particle pulses coming from the Linac, which would normally go and fill the DAΦNE collider, from the beam transfer line. The Linac repetition time is 20 ms, thus the power supply feeding the switchyard magnet must be able to ramp up and down in less than 20 ms and have a minimum ON flat top of 5 ms. In pulsed mode the flat top can be stretched to 0.96 s to allow a multi-pulse extraction. In addition this power supply must be able to operate as a conventional DC current generator. Finally as the Linac can produce both electrons and positrons it must be possible to reverse the polarity of the magnetic field, i.e. of the current.This paper describes the design and the commissioning of this power supply which was done by the CERN team.

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1 INTRODUCTION

In a complex of accelerators composed of many stages (Source, Linac, and Synchrotron) often the need arises to extract the circulating beam toward different users, measurement lines, fixed targets etc. This is done by using fast deflection magnets (kickers & septa) powered by fast pulsed power supplies. These supplies are expensive and cannot produce long flat pulses and their precision in amplitude is in the percent range. Since the time interval between two beam batches is of the order of few milliseconds, a medium speed, less expensive, pulsed power supply can be used. Moreover by using the modern switching IGBT technologies a precision in linearity, reproducibility relative to max better than 10^{-3} can be achieved.
The full specifications can be found in ref. [1, 2, 3].

2 GENERAL DESCRIPTION

2.1 Load characteristics

The load is a quadrupole magnet with the windings connected to form a dipole like magnet. Its inductance is L = 10.8 mH with an internal resistance R=43 mΩ.

2.2 Current requirements

The present working point of the LINAC is set at 510 MeV and at this energy the required current is 285 A. In the future the Linac energy is expected to increase to 800 MeV and the maximum required current will then be 447 A. It should also be possible to switch the polarity. The requested precision is +/- 1x 10^{-3}

2.3 Timing requirements

The power supply can work either in DC mode as a conventional magnet supply or in pulsed mode. In pulsed mode, start and stop pulses provided externally can generate power pulses with a rise and fall time of less than 10ms. The flat top can vary from 5ms to 960ms.

2.4 Control features

The power supply can be controlled either locally (mainly for specialists) or remotely from the control room via an RS422 interface with a MODBUS protocol.

3 CIRCUIT

A similar supply has been already described in [4]. For our application we have introduced some modifications to the bulk converter, in the booster charging circuit and in the H Bridge to enable the polarity change. Figure 1 shows the simplified circuit topology which consists of 3 main regulated stages. One can see that on this circuit the load appears galvanic isolated respect to the ground, in our application the load potential is defined by the ground leak protection circuit which is not shown here.

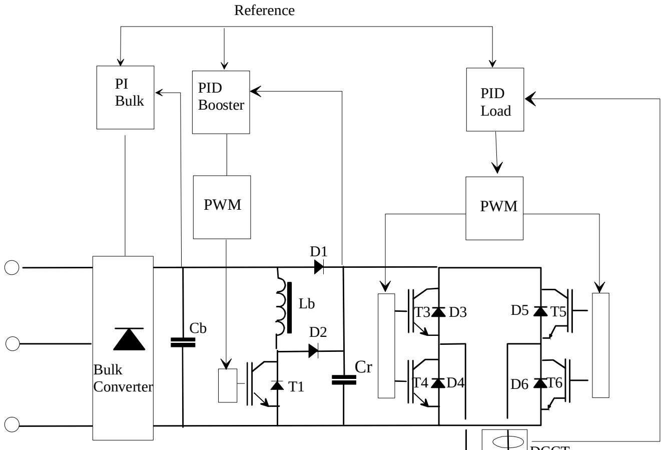

Figure 1. Simplified main circuit

3.1 The bulk supply

This is a 6 phase double star controlled rectifier which is able to deliver 500 A at voltages between 0 and 100 V. The filtering is done by a capacitor; Cb = 125mF, and an internal inductor (not shown in this circuit). The voltage regulation of this rectifier does not need a high precision but the internal resistance should be close to zero to be able to deliver the maximum current instantaneously to the load. The voltage is regulated proportionally to the demanded current on the load in order to minimize the power dissipated on the active half bridge.

3.2 The Booster supply

This circuit is a resonant network which charges the high voltage resonating capacitor Cr = 3mF from 0 to 1kV. This supply is activated only in pulsed mode to keep the charge prior to the pulses and to recover the energy lost during the fall time transition on the resistive parts of the circuit.

3.3 The H bridge

It is composed of 4 IGBTs mounted in an H configuration. Each IGBT has a free-wheel diode mounted internally. Depending on the polarity, only a half leg (top, bottom) of the bridge is active. This is the core regulator which is able to ensure the energy transfer to the load from the resonating capacitor, the flat top precision from the DC-link capacitor and the energy recovery from the load to the resonating capacitor at the end of the pulse. In DC mode its acts as a normal switching power supply.

4 WORKING PRINCIPLE

4.1 Phase1. Capacitor charge

In pulsed mode when the supply is ON, the bulk capacitor Cb is charged to a constant voltage proportional to the demanded current on the load. The PWM controlling the switch T1 closes. The current starts flowing exponentially in the inductor Lb with time constant Lb/Rb. After a time dependent on the amount of energy to be transferred the switch is opened and the energy accumulated in the inductor will be transferred to the capacitor Cr across the diode D2. When the voltage on the inductor becomes negative with respect to Vcr, the transfer stops and the PWM initiates another charge/discharge cycle and continues until the capacitor Cr has reached the required voltage value. During this time the H bridge is inactive and no current flows in the load.

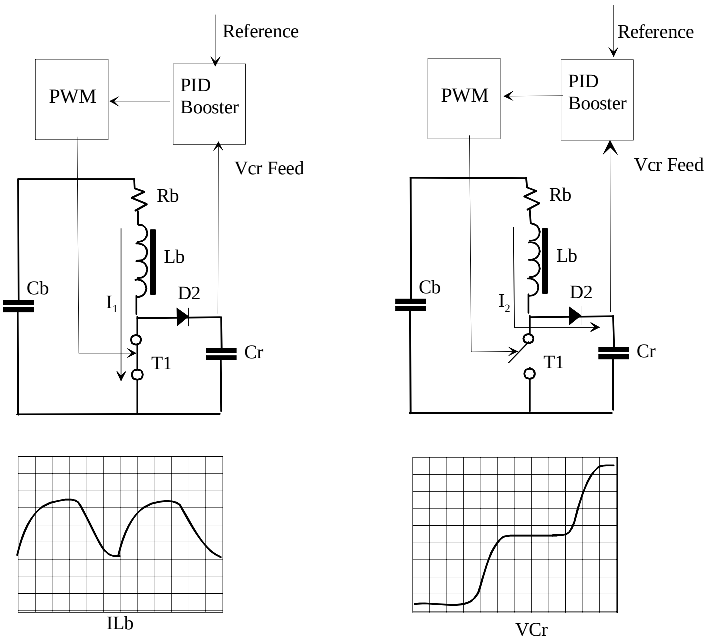

Figure 2. Equivalent circuit during phase1

4.2 Phase 2. Pulse rise

If a start pulse is received the Booster PWM stops. Depending on the requested polarity, switches 3/6 or 4/5 are closed (in Figure 3 T3 and T6 are closed). At this point the current starts flowing in the resonant circuit consisting of Cr and L_{load}. The current in the load increases sinusoidally until the voltage on the capacitor Cr become smaller than the Voltage on Cb.

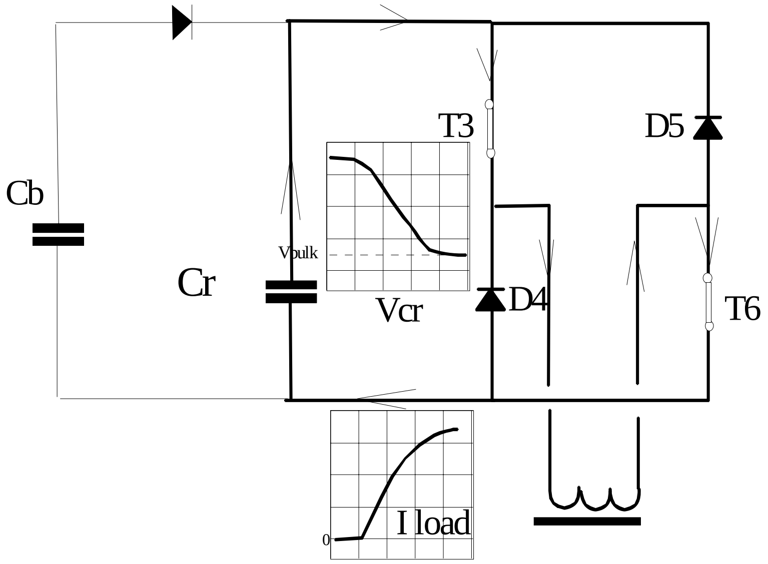

Figure 3. Pulse rise on the load

4.3 Phase 3. Flat top regulation

When the current on the load reaches its maximum the diode D1 starts to drain the current from the bulk capacitor. To maintain a flap top to PWM controlling the top active switch (T3) starts to regulate the current in the load depending on the signal received by the PID while the bottom active switch (T6) is kept closed until a stop pulse is received.

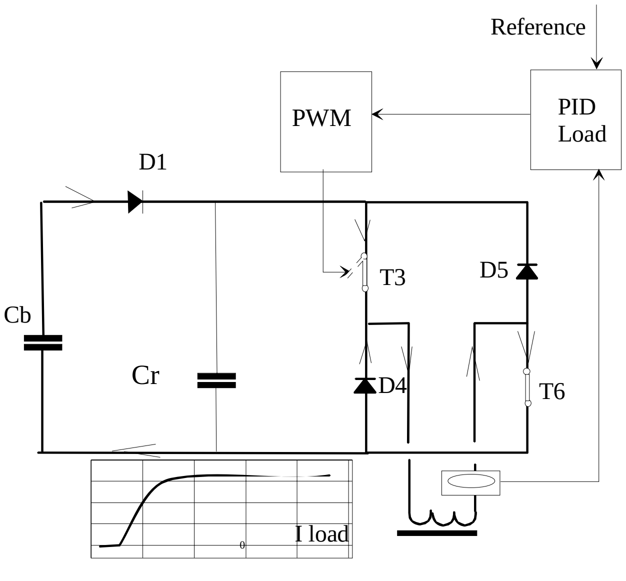

Figure 4. Flat top regulation

4.4 Phase 4. Fall time & Energy recovery

When a stop pulse is received both switches (T3 & T6) are opened. Then the current flowing in the load starts to circulate across the diodes D4 & D5 and the energy stored in the load is recovered in the Cr capacitor which is theoretically re-charged to its initial value. During this process a certain amount of energy is lost on the internal resistor of the load, the transmission cable and the diodes hence the booster PWM is restarted to compensate for these losses before the next start pulse arrives.

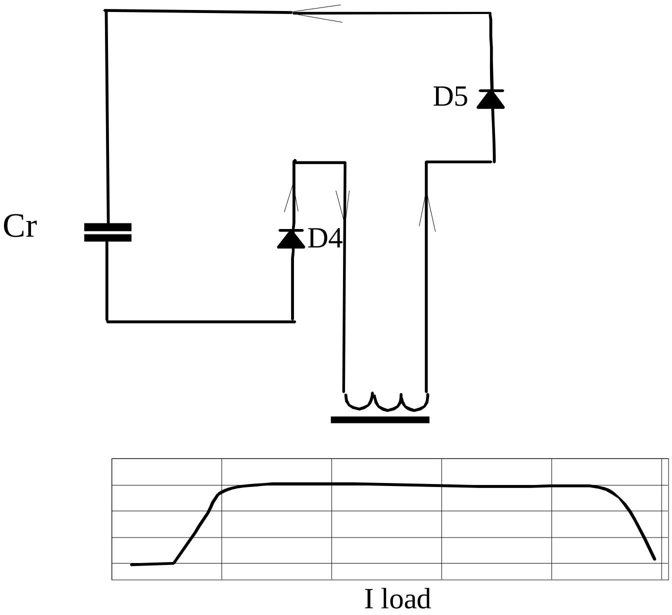

Figure 5. End pulse Energy recovery

5 PARAMETERS CALCULATION

The Load inductance and resistance are defined by the magnet characteristics:

L = 10.8 mH; R = 43 mΩ.

The transmission lines are more or less also defined by the distance from the magnet to the power supply, let's assume R_{cable} = 5 mΩ.

To obtain a rise time less than 10 ms as specified, the resonating capacitor must have a value less than 3.75 mF (neglecting the internal resistance).

$$t = \frac{\pi \cdot \sqrt{L \cdot C}}{2} \leq 10ms \qquad (1)$$

C = 3.75mF

A suitable industrial capacitor available on the market was a 3mF, 1.8 kV, 420 A r.m.s. oil filled component from EPCOS. With these values: C = 3mF; L = 10.8mH the capacitor must be charged theoretically to 853 V to produce 450 A on the load and the rise and fall time is T_{rf} = 8.9 ms..

$$Vc = I_{MAX} \cdot \sqrt{\frac{L}{C}} \qquad (2)$$

Vc = 853V

5.1 Evaluation of losses

The energy balance from the start to flat top can be evaluated as follows:

$$E_{C,0} = E_{L,\mathrm{Im}} + E_{R,tr} + E_{IGBT} + E_{DC} \qquad (3)$$

Where:

$$E_{C,0} = \frac{1}{2} C V_{C,0}^{2} \qquad (3.1)$$

is the energy stored in C before pulsing.

$$E_{L,\mathrm{Im}} = \frac{1}{2} L I_M^2 \qquad (3.2)$$

is the energy stored in the magnet when Imax is flowing.

$$E_{R,tr} = \frac{\pi \sqrt{LC}}{4} \cdot R I_{Max}^2 \qquad (3.3)$$

is the integral energy lost in resistances during the pulse rise.

$$E_{IGBT} = 2 \cdot V_{IGBT} \cdot I_{Max} \cdot \sqrt{LC} \qquad (3.4)$$

is the integral energy lost on the IGBT switches during the pulse rise. (V_{IGBT} = 2.2V).

$$E_{DC} = \frac{1}{2} C V_{DC}^2 \qquad (3.5)$$

Is the energy remaining in the capacitor when a DC flat top is established assuming that

$$V_{DC} = RI_{max} + 2V_{IGBT}$$

When solving equation (3) with the real parameters the capacitor voltage must be 874 V to obtain 450 A on the magnet.

Similarly we can calculate the energy balance at the end of the pulse by replacing the voltage drop on the IGBT(2.2V) by the voltage drop on the diodes(0.6 V)

The equation becomes

$$E_{C,end} = E_{L,\mathrm{Im}} - E_{R.tf} + E_{Diodes} + E_{DC} \qquad (4)$$

At the end of the pulse the recovered voltage on the capacitor will be 835 V, which corresponds to an energy loss of ~ 100 J.

This energy must be compensated for by the booster converter before initiating another cycle.

5.2 Booster Design

An iron inductor with the following parameters: Lb = 1.7 mH, Rb = 50mΩ, Ibmax = 500 A was available

The energy which can be transferred to the capacitor Cr from the booster inductor is :

$$E_{Booster} = \frac{1}{2} L I_{IB\max}^2 \qquad (5)$$

If we fix the maximum operating current in the inductor to 300 A, then the energy transferred in one booster cycle is. ~76 J.

Using equation (1) the transfer time is:

$$T_{\mathrm{Transfer}} = 3.5 \text{ ms}$$

The maximum bulk voltage is 100 V. The current in the inductor when energized will increase according to the equation (6) and the time necessary to reach 300A is:

$$T_{\mathrm{fill}} \sim 7\text{ms}.$$

$$I_{Lb} = \frac{V_{bulk} - (V_{Diode} + V_{IGBT})}{R_{Booster}} \cdot \left(1 - e^{-\frac{R_b t}{L_B}}\right) \qquad (6)$$

Thus the minimum period for an energize/transfer booster cycle is ~10.5 ms.

For this reason and also to cope with the Foucault currents in the iron we choose a PWM booster frequency F_{er} = 100Hz. The minimum time between the falling and the rising edge of two pulses is 30ms and with this circuit we can compensate the energy lost in the transfer from the magnet to the resonating capacitor in less than 20 ms.

5.3 Thermal Design

A full study of the thermal behaviour and thermal stress of the H bridge has been carried out in [5]. This study lead to the choice of the bridge PWM frequency F_H = 6 kHz and to the dimensioning of the air cooled heat sink installed in the power supply. It has also demonstrated that the ΔT on the IGBT junctions does not exceed 15 ^oC when pulsed. The estimated life time is of the order of 10^4 hours in the worst case (pulsed mode 1 Hz).

6 FINAL PARAMETERS

Table 1. Main parameters

Item	Mn	Max	Units
Load Current	0	500	A
Rise time	-	8.9	ms
Fall time	-	8.9	ms
Voltage bulk	0	100	V
Voltage Cr Booster	0	1000	V
Power on the load	0	12.5	kW
Power on supply	0	50	kW
Heat Sink Temperature	0	70	^oC
Booster Frequency	-	100	Hz
H bridge Frequency	-	6	kHz
Regulation precision	-	+/- $5x10^{-4}$	Imax relative
Regulation Linearity	-	+/- $1x10^{-3}$	Imax relative
Ripple (5 kHz)	-	+/- $1x10^{-3}$	Imax relative
Resonating capacitor	-	C_N = 3	mF
Cr	-	U_{NDC} = 1890	V
	-	U_{iAC} = 1650	V
	-	I_N = 420(50HZ)	A
	-	Tanδo=2x10-4	-
IGBT		V_{CES}=1200	V
(DIM800 DDM12-A000)		$V_{CE(sat}$=2.2	V
		Ic=800	A
Diode//IGBT		Icpk=1600	A
		I_F=800	A
		V_{RRM}=1400	V
D1-D2(DS502ST)		I_F=866	A
		I_{FSM}=8000	A
DCCT	0	Range +/- 505	A
Hazemeyer		Bw= 10	kHz
		Ratioε< 5	ppm
		Noise σ < 20	ppm

7 CONTROLS AND REGULATION

To save time and reduce cost, the power supply control is a G64bus based system which uses CERN standard cards series widely used in the PS accelerator complex. The microprocessor (6809) firmware provides the timing control, the remote control and the main-interface with the supply.
There are 3 analog regulators on board.
One is for the Bulk supply which is a six phase six thyristor angle controlled rectifier. The regulator acts as a voltage source with a maximum current of 500 A.
The second is a switching resonating charge transfer supply. Its regulator is based on a single PWM which also acts as a voltage regulator with a max current limited to 300 A.
The third one is a mix between a resonating pulsed supply and a DC switching supply. The regulator acts as a current source up to 500 A with 100V as a maximum voltage.

8 TEST & COMMISSIONING

One power supply has been built in 2005 and tested on a test load at CERN in April-May 2006.

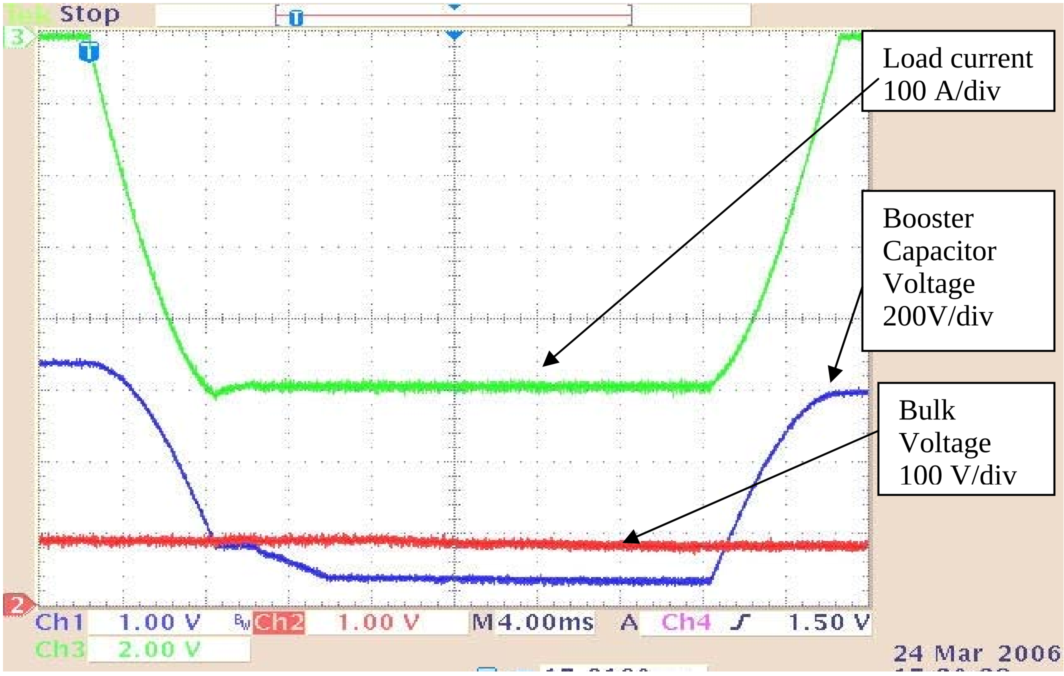

Figure 6. 500 A negative pulse on the load

Figure 6 shows a 500 A pulse (upper trace) with 8 ms rise & fall time and a 24 ms flat top.
The lower trace shows the voltage behaviour on the resonating capacitor while the straight line shows the voltage on the bulk capacitor. It is interesting to remark that the voltage on the resonating capacitor was overcompensated before pulsing because the current on the load had reached the required value before the voltage of the capacitor had become equal to the voltage on the bulk. Then the energy for the first 7 ms flat top still come from the resonating capacitor and not from the bulk converter. This can be adjusted by changing the linear coefficient between the reference and the booster voltage regulation. Even in this wrong condition one can see that the bridge regulator has worked perfectly.

Figure 7. 280 A positive pulse on the load

Figure 7 shows a perfectly compensated 280A positive pulse on the load. This also demonstrates the capability to change the current polarity on the load.

Figure 8 shows the current pulses generated in the booster inductor during the idle time between two successive load pulses to recover the energy losses dues to the resistive parts of the resonating circuit. In this figure the booster frequency was ~300 Hz. To obtain the best energy transfer we set this frequency to 100Hz in the final version.

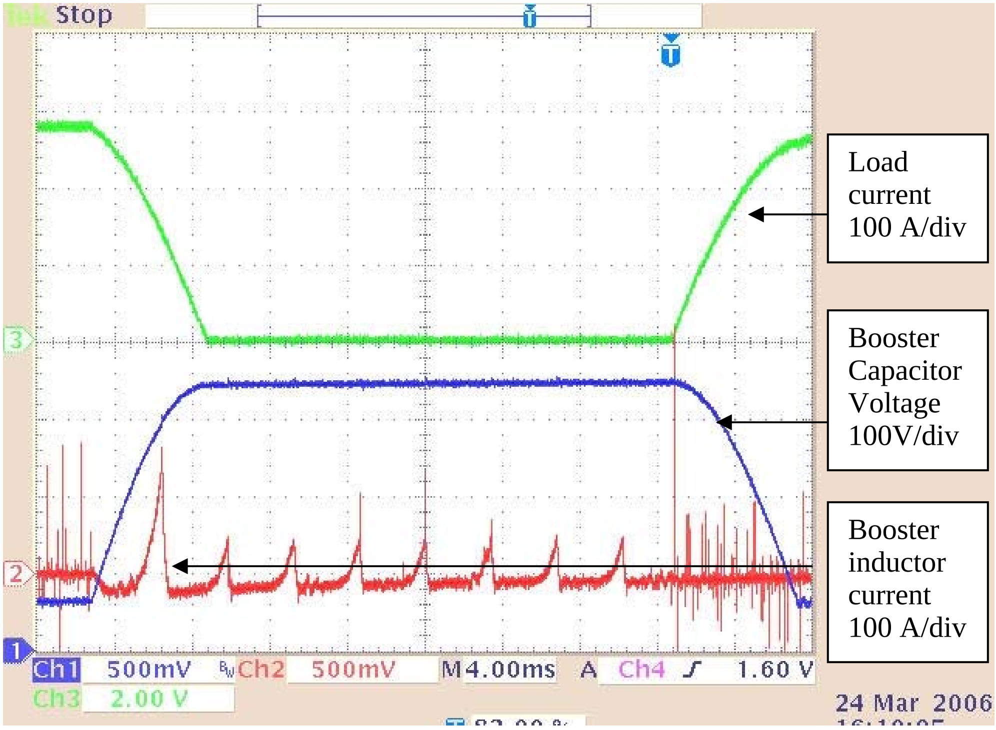

Figure 8. Current in the booster inductor used to compensate the losses between two consecutive pulses.

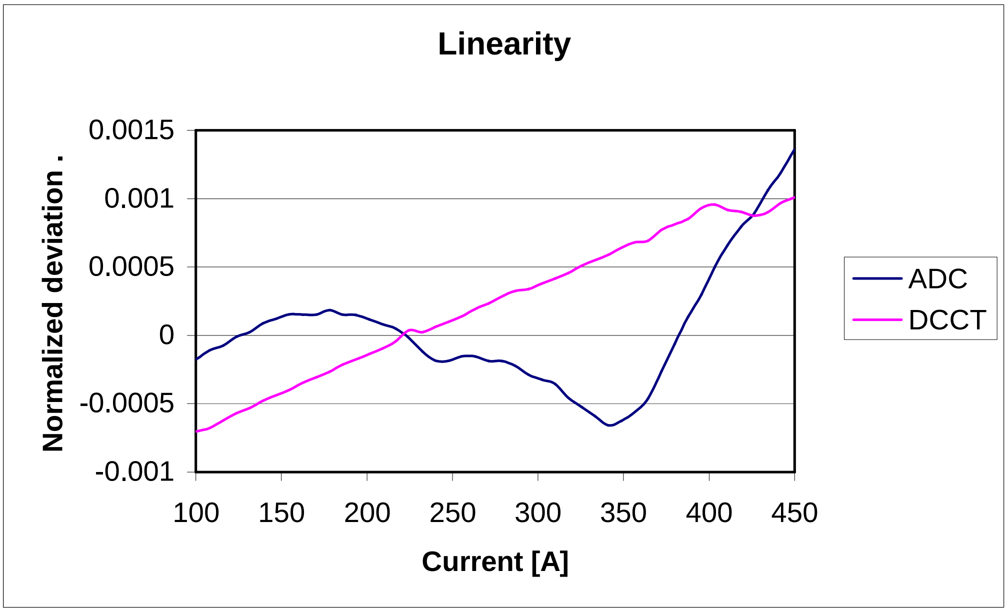

Figure 9. Measured linearity in the operating range with the internal ADC & an external DCCT.
(Courtesy of Frascati team)

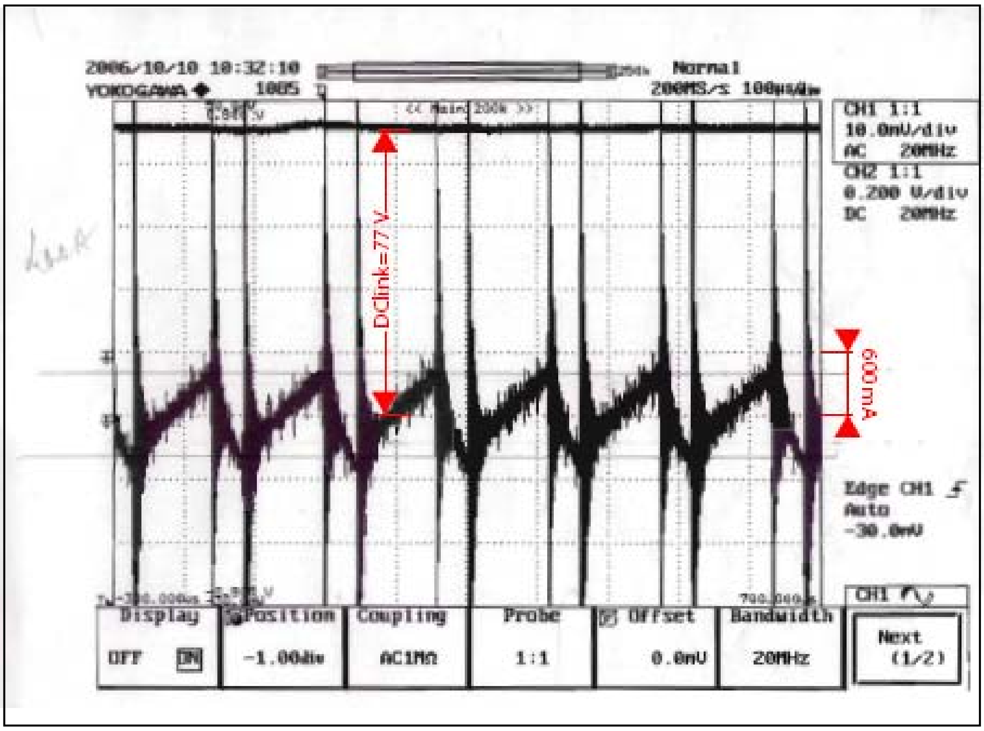

Figure 10. Measured current ripple on the load at 400 A.
(Courtesy of Frascati team)

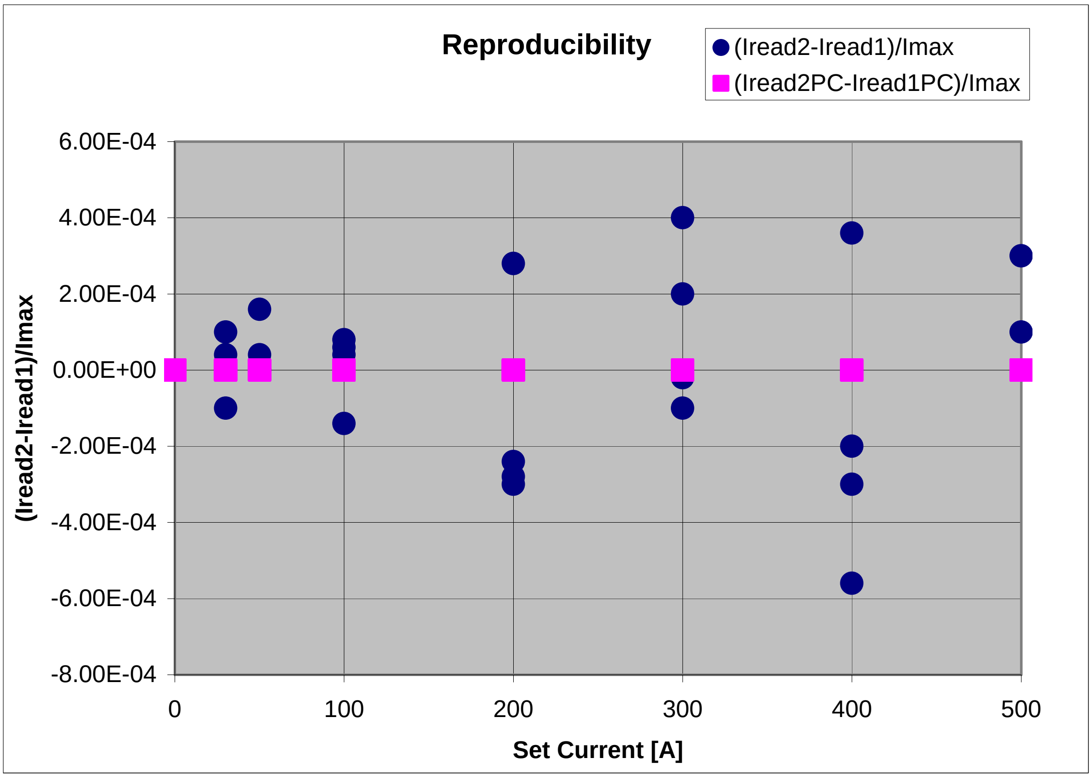

Figure 11. Current reproducibility in pulsed mode
(Courtesy of Frascati team)

Figure 9 shows the linearity compared between a requested reference value and the read-back current on the load trough the internal 15bits ADC and an external DCCT. The linearity deviation does not exceed in both cases +/- $1x10^{-3}$.
Figure 10 shows the ripple on the load current. One can see the ripple does not exceed 800mA which corresponds to+/- $1x10^{-3}$ in absolute. Finally Figure 11 shows the reproducibility for different requested value (5 measurements for each point).The exhibited reproducibility is better than +/- $5x10^{-4}$relative to the max value.

9 CONCLUSION

The challenge was to design and build a robust, compact and versatile converter in a very short time (6 months) with the minimum effort in human resources and at the minimum cost. Some time the adopted solutions were a compromise between the best and a reasonably good technical choice (i.e. Air cooling instead of water cooling). To reduce the cost we have used some parts recuperated from old LEAR power converters. Nevertheless the final result is a success. The schedule was respected. The requested specifications were fulfilled and the cost was maintained under 50 kEuro which is very cheap for this kind of power converter. In June 2006 this power converter was successfully commissioned at the DAΦNE LINAC injector in Frascati where it is daily used in operation without problems since then.

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