

Precision power supplies

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Introduction

The purpose of this document is to provide background information about the design and performance of two specialist magnet power supplies used at Daresbury Laboratory which are designed for extremely demanding applications .

Instructions for student investigations into the behaviour of precision supplies are provided in the companion document " Power supply Testing and Specification".

Acknowledgements and references are provided at the end of this document. Photocopies of most of these references can be made available.

General background

DARESBUY LABORATORY

The photograph shown below gives an aerial view of the synchrotron radiation source at Daresbury Laboratory, situated near Warrington in Cheshire.

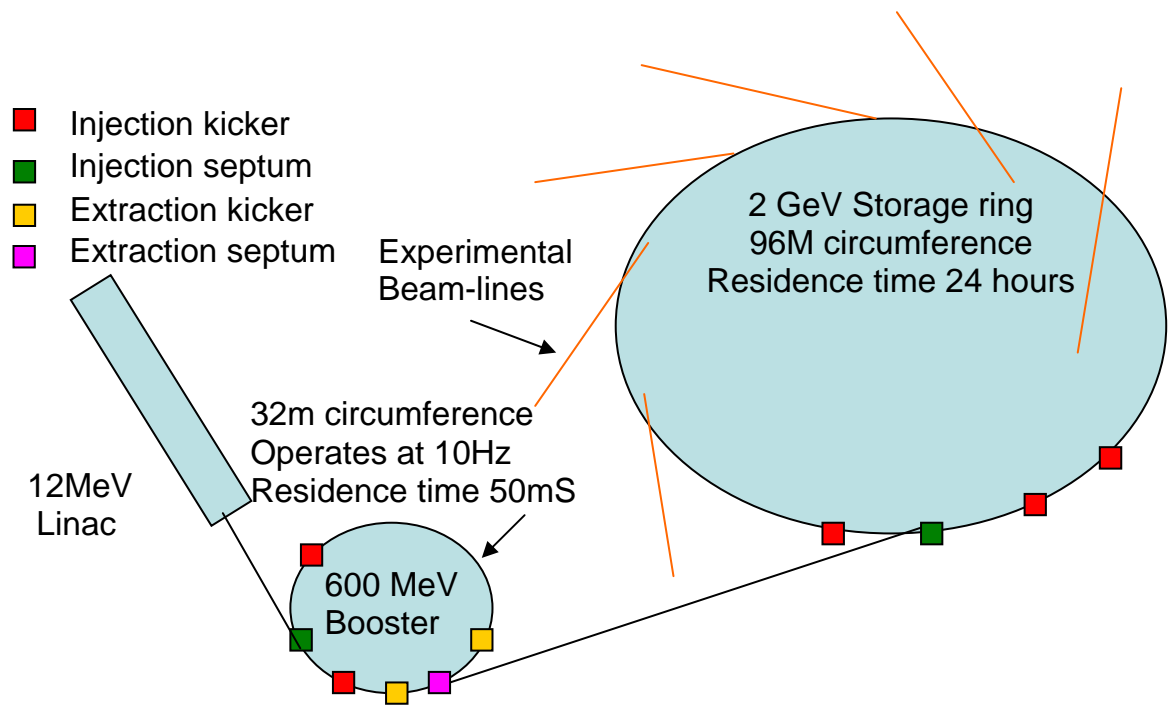


In this facility a beam of high energy electrons is stored in a circular beam tube, causing the emission of intense ultra violet and X-ray radiation.

The synchrotron radiation source consists of a sequentially linked suite of three electron accelerators:

- A 12 MeV Linear Accelerator
- A 600 MeV (10 Hz) Booster Synchrotron
- A 2 GeV main storage ring

The physical arrangement is shown below.



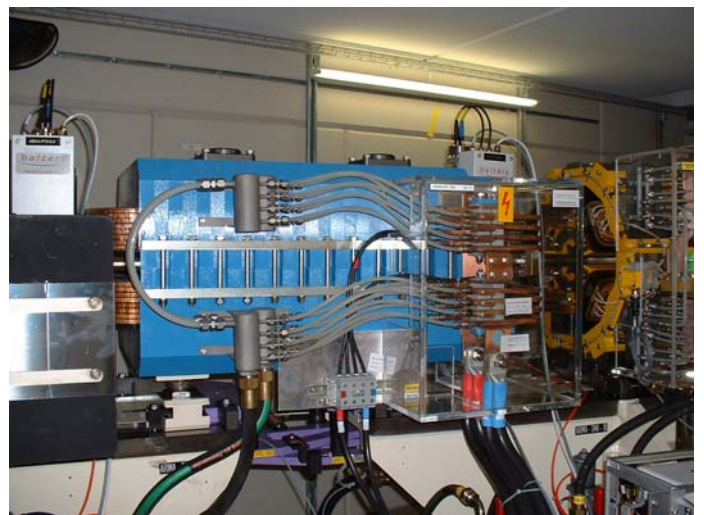
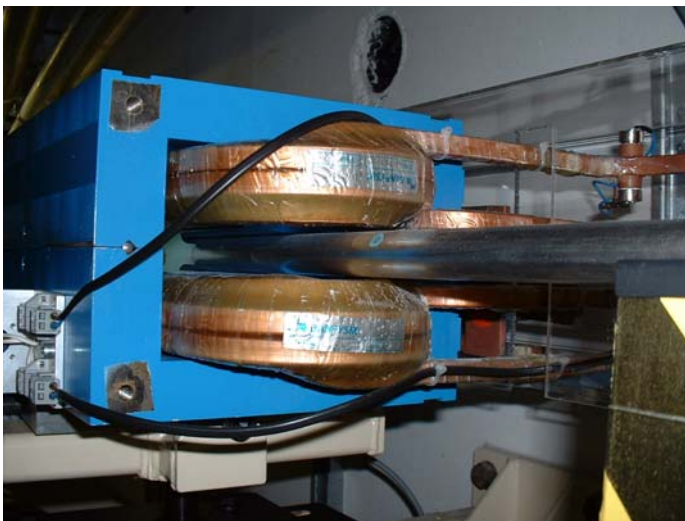
This involves using over 400 DC (and AC) power supplies for the magnets which focus, bend and steer the electron beam.

The power supplies we are studying are for the electromagnets which bend the beam into its circular trajectory and for the magnet system which injects new beam into the ring.

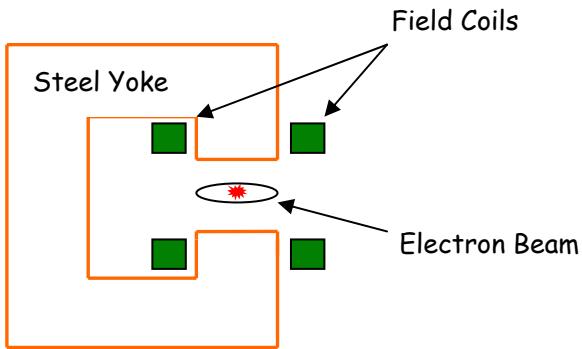
The Dipole Magnets

The purpose of the dipoles is mainly to constrain the beam in a circular trajectory.

A typical Dipole is shown below from two viewpoints:



Schematically, we have:



Specification of a storage ring Dipole magnet

Some typical parameters are:

- Dipole field 1.2T
- Length 1.44m
- Magnet gap 50mm
- "Good Field" (hor x ver) 60 mm x 40mm

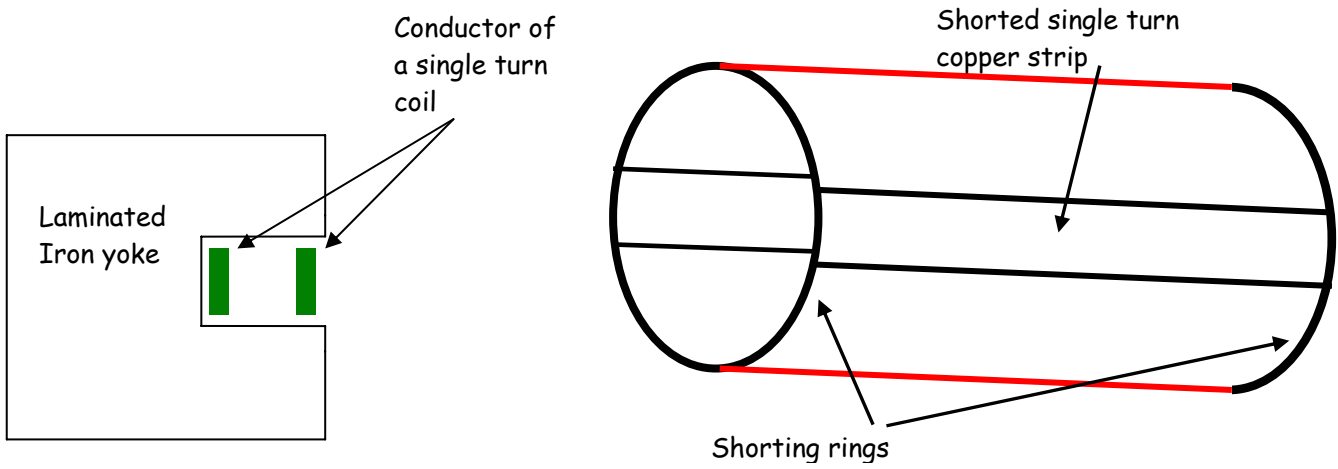
The Beam injection system

This consists of pulsed magnets with their associated power supplies; the " Kickers " which briefly move the established beam into the path of the injected beam and the "Septum" which deflects the injected beam into the correct trajectory to join the established beam.

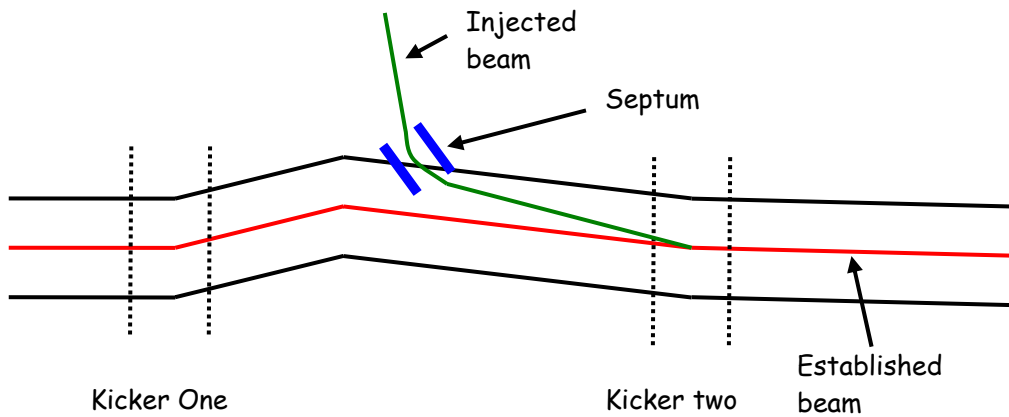
The pictures show a kicker and a septum enclosure installed in the beam line.



Schematic diagrams of a septum and a kicker magnet are also shown:

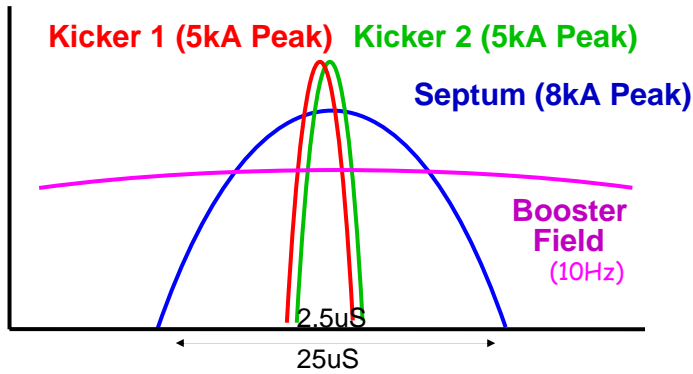


The process of injection is shown diagrammatically below:



More precisely, at maximum booster field, the septum is fired ready to deflect the new beam. At peak septum field, the storage ring injector kickers fire and push any established beam towards the septum, so that the incoming beam is close to the stored beam. The kicker field then switches off before the injected beam can hit the septum.

The sequence is shown below.



General Requirements for the Magnet power supplies

The supplies for the storage ring bending magnets are essentially highly stabilised D.C. current sources in the range of several hundred kilowatts to several megawatts. Those for the injectors have high dynamic requirements (a large current increase in a short time) and need to provide a well defined current pulse shape (eg sinusoidal).

Since **reliability** is of paramount importance, the supplies should be built in a simple and straightforward manner, concentrating on :

- reliability
- avoiding electromagnetic components
- ease of repair
- simple structure
- high degree of standardisation of components
- identical standards for control system interfaces.
- modularity (the n+1 philosophy entails the provision of an extra module so that output is not significantly affected by the failure of one)

The tolerances requested of a power supply are dictated by the quality of the machine optics to be achieved.

These requirements are translated into maximum allowable variations in output current or voltage and can be summarised as:

- Absolute accuracy
This is controlled by the quality of the chosen current reading transducer. Essentially it is a statement that the metered output value is correct.

- Linearity

This is the deviation of the actual current from a reference line specified during calibration.

- Following error

This describes the error in the current during a current change and is the difference between the set current and the actual current.

- Overshoot

In case of abrupt required changes in current the overshoot has to be less than a specified value such that

$$\frac{\Delta I_i}{\Delta I_s} \leq \text{specified} \quad (\Delta I_i \text{ is the peak to peak amplitude}$$

after first reaching the new setting and ΔI_s is the step change of the setting value).

- Resolution

Determined by the maximum number of bits of the DAC used in the control system. In a 16 bit system the resolution is 1.5×10^{-5} (referred to the nominal current). Basically it is the smallest change that can be made to the current.

- Short and long term current stability

The short term stability could be regarded as the variation in output over a few hours. Long term covers a period of about 24 hours.

- Current ripple

This needs to be minimised. It is generated at the AC to DC conversion stage. A 12 pulse 2 x 3 phase bridge (shown later) generates a fundamental of 600 Hz. A filter stage tuned to this frequency can reduce the current ripple to < 100 ppm.

In summary :

The important performance characteristics of the power supplies are:

- ❖ Short term stability (including noise), for time spans of less than 8 hours.
- ❖ Absolute accuracy of the DC value in steady state.
- ❖ Reproducibility over time and shut downs.

For technical details and practical definitions, see Annex One

Case study one: The Kicker (and Septum) magnet power supply

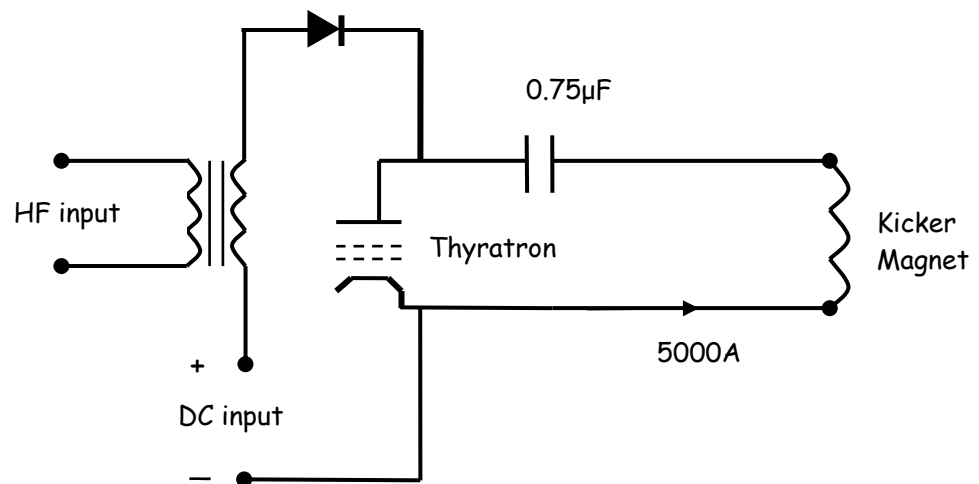
Kicker Specification

The injection kickers are required to produce a 2 mrad (0.115°) deflection in the beam. It can be shown that this requires a magnetic field of 10mT over the active length of the magnet. The field is generated by a 2.3μs current pulse in a pair of copper conductors, as shown in the diagram earlier.

the separation between these conductors needs to be at least 140mm so that the beam does not strike them and this means that the required maximum current of the pulse is 5000A.

Basic circuit idea

The original circuit idea is shown below:



Calculations:

The pulse width T is given by:

$$T = \pi\sqrt{LC} \quad (T \text{ in microseconds, } L \text{ in microhenries and } C \text{ in microfarads})$$
$$\therefore L = \frac{T^2}{\pi^2 C}$$
$$L = 0.684 \mu H$$

This represents the total circuit inductance.

The impedance of this circuit is given by

$$Z = \sqrt{\frac{L}{C}} = 0.955\Omega$$

From this we can calculate that for a peak primary current of 5000A we need the 0.75 μ F capacitor to be charged to a voltage of 4775 V (from $I \times Z$). An A.C. charging circuit as shown above enabled a 500v D.C. supply to be used.

Circuit operation

Very briefly, the D.C. supply charges up the capacitor, which continues to be charged to the required voltage by the application of an A.C. current to the input transformer (rectified by the diode). The D.C. supply tops up the charge after every firing of the Thyatron, which essentially discharges the capacitor briefly through the kicker field coil to produce the required pulse.

This design fulfilled the original requirement criteria, producing a 5000A pulsed current with a half sine wave pulse of approximately 2.3 μ s. The maximum pulse repetition rate was 5Hz with a firing jitter better than 10nS.

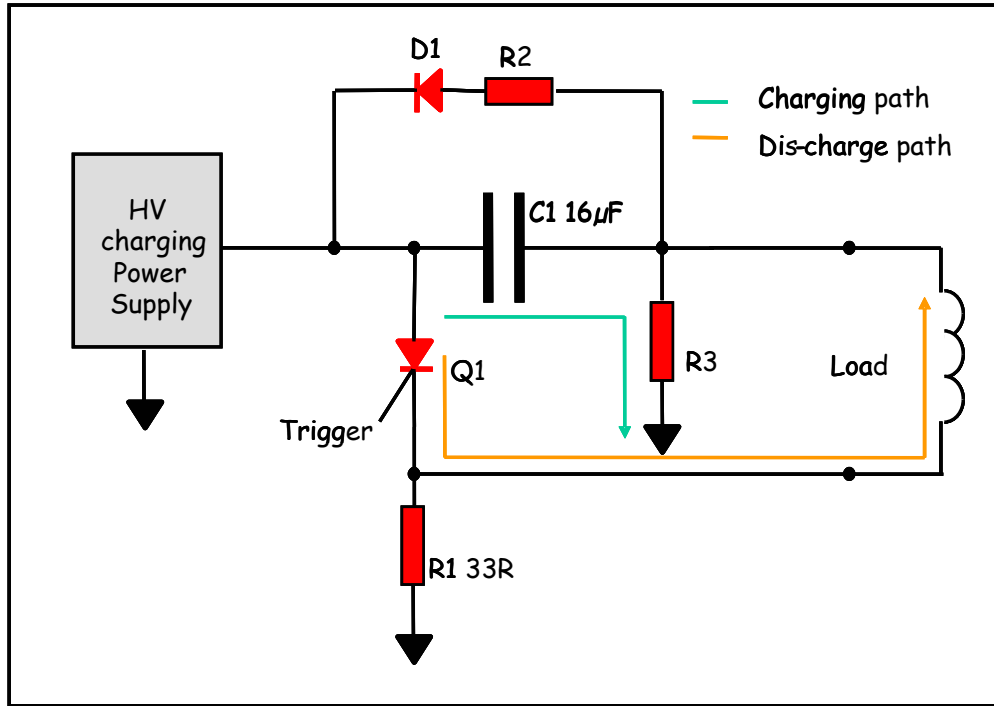
A similar design was used for the septum power supply, with a requirement for a 25 μ s pulse of amplitude 8000A.

This needed a 2 μ F capacitor charged to over 8,000 volts.

Disadvantages of the above power supplies:

- Thyatron valves are expensive
- Lengthy repair times
- Specification needs upgrading for future applications (Diamond)
- Fails new EU safety standards

Circuit diagram and picture of the replacement power supply:

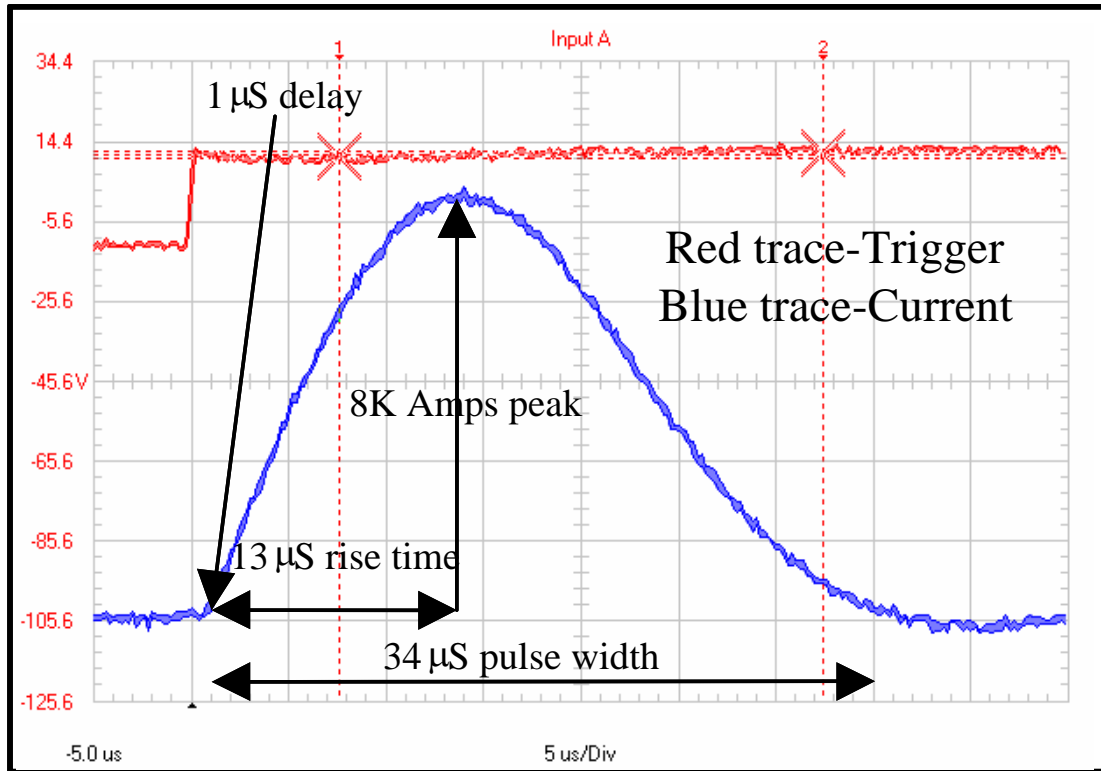


Thyristor switched pulse power supply

Advantages of the replacement power supply:

- Designed for ease of maintenance
- Meets EU safety standards
- Modular, easily replaceable units
- Uses solid state thyristor technology
- Specification improved, ie jitter < 2ns

Typical output pulse



Output Current Response of Solid-State Pulse Power Supply (Septum power supply)

Case Study Two : The DC supplies for Dipole bending magnets

The pictures below show the main parts of a typical supply set-up:



Power Supply Room



Dipole Supply cabinet



Interior views of dipole cabinet, showing output inductor

The SRS (Synchrotron Radiation Source) storage ring magnet lattice at Daresbury consists of series chains of dipole, quadrupole, sextupole and octupole magnets and the beam energy is increased from 600 MeV to 2GeV by ramping the currents in the magnets under computer control.

The Power Converters

The dipoles have 16 magnets in series and are fed from power converters rated at 500V, 1500A.

There is a midpoint earthing system which returns a power earth from the midpoint of the magnet chain to the power converter, so that the positive output terminal will be at +250V and the negative terminal at - 250V.

The rectifier has a 12 pulse behaviour and comprises two three phase fully controlled thyristor bridges, with the outputs paralleled. The bridges are fed from two identical rectifier transformers configured to give the 30° phase shift required for 12 pulse operation.

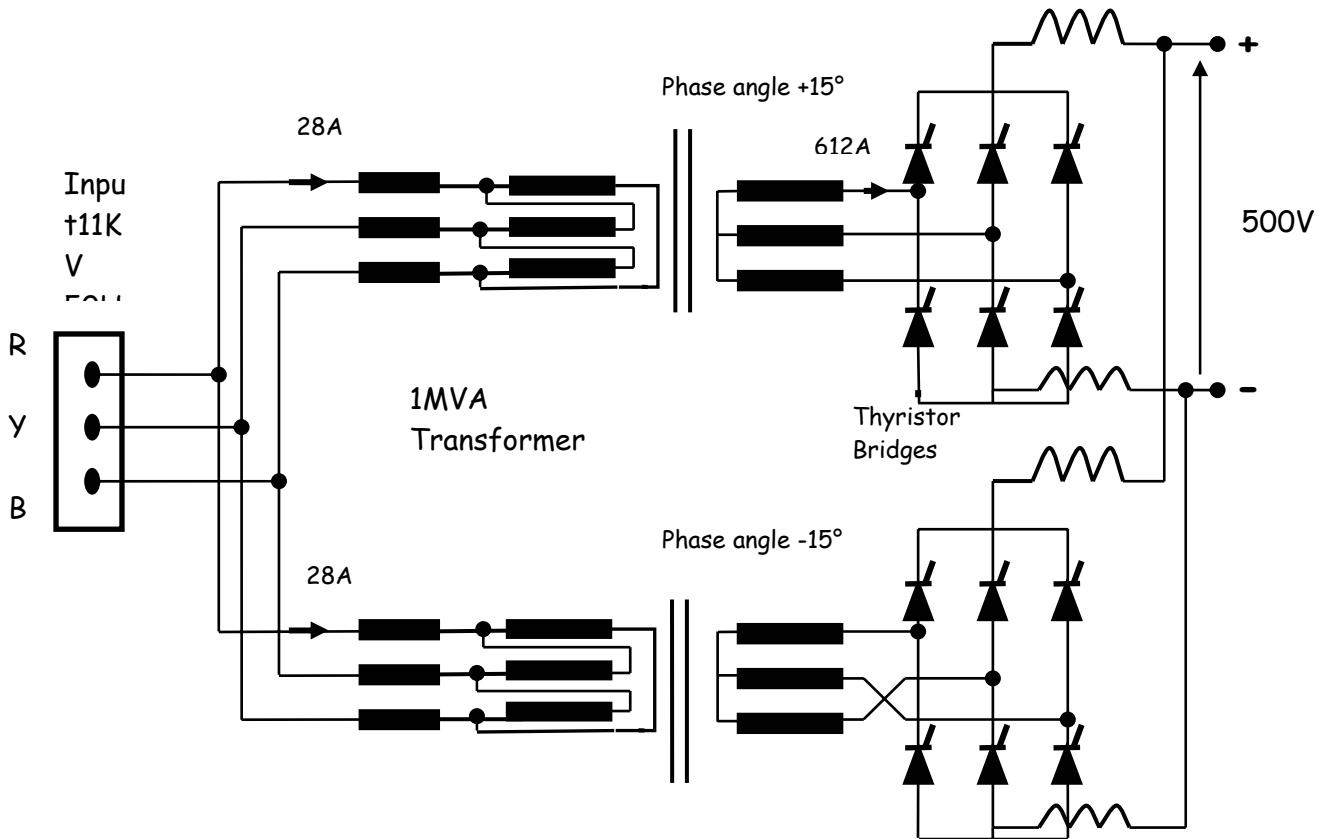
The Output Rating for the Rectifier is:

- Maximum continuous output current 1500A
- Maximum continuous output voltage at maximum current 500 V
- Maximum continuous output power 750 KW

Thyristor Ratings (WESTCODE N510CH20)

- Average current 250A
- Min repetitive voltage forward and reverse 2000V
- Min surge current rating 20000A

Circuit Diagram of the Power Converters



(For information about the operation of this circuit, consult reference 9)

Filters and transient suppression

A transient suppression network is connected through an auxiliary diode bridge at the AC side of the converter.

The output ripple is reduced by means of a passive filter, which consists of a damped LC circuit.

- Inductors (rated at 750A), inductance 4.7mH
- Capacitors 7.42 mF and 1.48 mF
- Damping resistor, 0.22Ω.

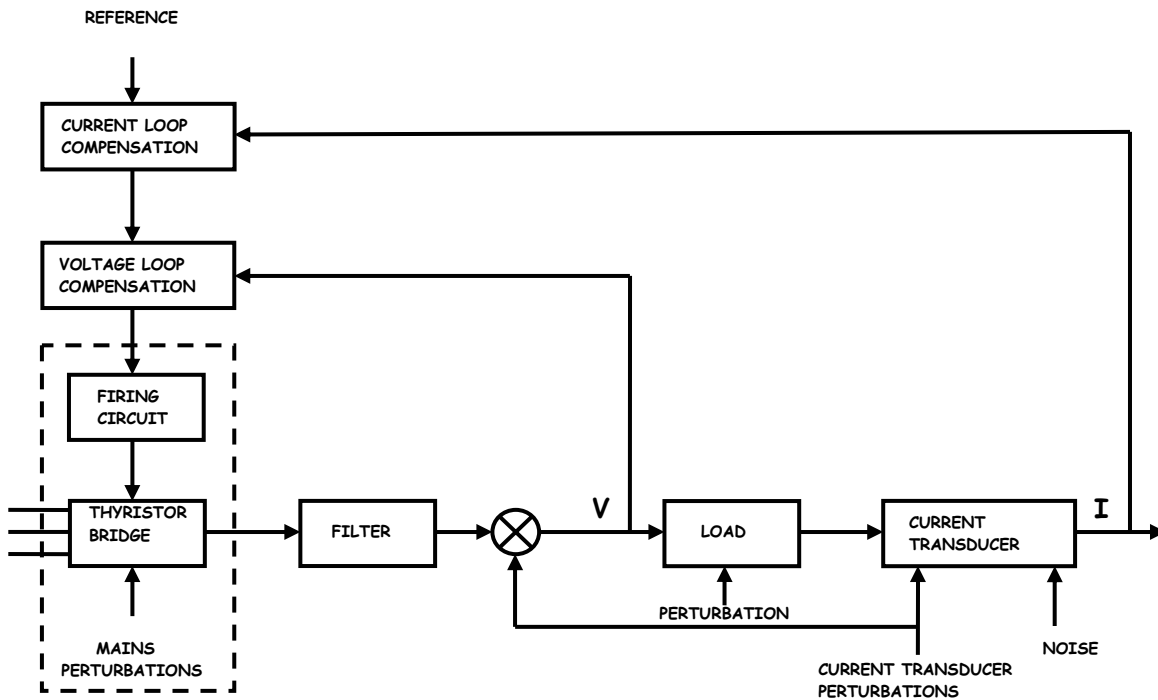
Output current is measured using a DC current transformer. (With an additional one for comparison purposes).

Control of overall technical performance

The technical performance, such as the output voltage and current **stability** are achieved by the use of high precision electronics driven by the output from the two DC current transformers. This performance can only be obtained by the introduction of closed loop control around the circuit

described earlier. Essentially the electronics automatically controls variation in the output voltage and current in order to meet the required specification.

BLOCK DIAGRAM OF THE CONTROL SYSTEM



Description of the control system

The controlled quantities are the voltage and current. the voltage is measured across the filter output and the current is measured using a zero flux DC current transformer, converted into a voltage using a precision shunt resistor.

The perturbations to the output current come from three main sources; the mains network, the current transducer and the load (the magnets).

The mains perturbations cause a variation in the filter output voltage which is fed back into the voltage loop compensation circuitry. This generates a command signal for the thyristor firing system and produces a nearly perfect voltage source at the load. (Since the voltage change is measured before the load this gives a rapid response to transient perturbations - the **fast** loop).

The current transducer and the load magnets cause perturbations in the load current and the transducer output provides the signal for the low frequency command of the system via the current loop compensation circuitry. (The **slow** loop).

The design of the closed loop voltage compensation involves a phase shift and integration although actual compensation is more complex than this.

The current loop compensation circuitry includes a filter and limiter which essentially gives maximum and minimum operating levels for the voltage source.

On-going developments in power supply controls

The precision of existing power supplies depends mainly on the precision of Analogue to Digital converters and current to voltage transformations. ADCs with high conversion rates produce noise on the output. This can be reduced to 1ppm by suitable filters. Absolute precision is determined by the voltage reference used for conversion. To reach the necessary stability the reference has to be thermally stabilised.

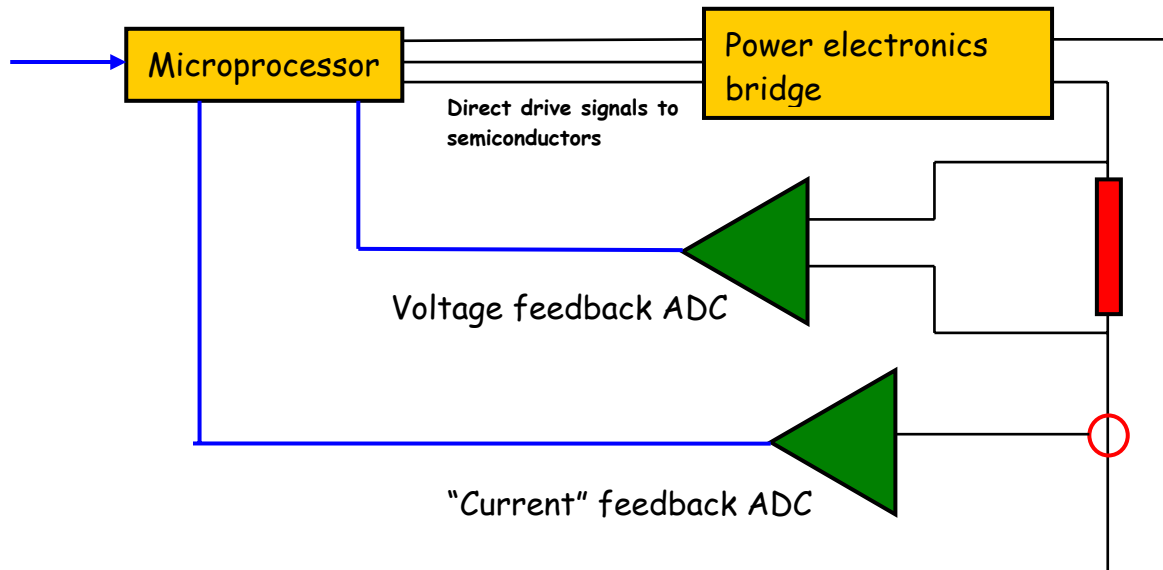
The development of precision DCCTs and shunt resistors with temperature coefficients of less than 2ppm/K and low self heating have made it possible to produce power supplies with stability and reproducibility of better than 100 ppm .

The Hitec Topacc T20-8 is a commercially available DCCT with the following specification:

Rated current 1000A
Rated output voltage 10V
Ratio Error 25ppm
vs temp 1ppm
vs time 0.5 ppm/month
vs time 5ppm/year

Further improvements are achievable by reducing the amount of analogue circuitry in the feedback control system.

A schematic of a fully digital control system (in use at the Swiss Light Source) is shown below:



Digital control system (SLS)

Concluding comments

The designers of particle accelerators look for ways to ensure stability of the position of the particle beam.

A major factor in achieving this objective is the stability of the magnet power supplies.

In the past it was necessary to connect magnets in series to ensure the similarity of the performance of groups of magnets. Now, however with improvements in reproducibility between magnets and similar improvements in control technology, it is feasible to have each magnet individually supplied with current.

Present computer systems are capable of the speed and capacity required to carry out the complex real time analysis of the complete system and initiate appropriate control instructions. It may even become possible to provide differential beam positioning accuracy to different sectors of the beam.

Acknowledgements

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Annex One

Performance specification

All power converters will be measured against the following performance parameters

Long-term Stability (8 hrs to 6 mths)

50 ppm

200ppm

Short-term Stability (100 sec to 8 hrs)

10ppm

100ppm

Resolution (minimum)

18 bit

16 bit

Ripple (perturbation error)

<10ppm

<100ppm

Reproducibility

10ppm

100ppm

Performance Specification for Power Converters

Output current ripple - the specified current ripple and noise is gauged on that required for other accelerators. Their impact on the closed orbit of the chosen lattice needs to be assessed, taking into account the filtering effects of the vacuum chamber and the magnets. The ripple frequency and amplitude will depend on the power converter technology employed.

Reproducibility- after a period of interruption of 24 hours with all the electronics turned off, the power converter should be capable of returning to within 10ppm or 100ppm, depending on magnet type, of the former value after one hour with the same reference.

Short term stability - this depends on the control technology employed, but a major contributor to this is the current transducer. It is understood that actual precision can only be measured with warm electronics and there will be an initial period of settling time. The power converter controls will maintain warm electronics to minimise drift at turn-on and actual short term stability will be measured over an eight hour period. The drift will then be a result of the self-heating of the current transducer burden resistor, the input reference and the conversion (A to D or D to A).

Long term stability - again governed by the output transducer and the conversion quality. The absolute precision of the ADC conversion is related to its internal reference voltage. Any drift in this reference will effect the precision, similar effects are seen due to ageing of the burden resistor for the current transducer. These can be avoided with regular calibration checks.

Resolution - conversion dictates the resolution, but with high sampling rates necessary to achieve the dynamic performance, noise will always show on the output signal. It is expected that some filtering may be required to ensure step changes on the output, can be both set and monitored at the 10ppm and 100ppm level, relating to magnet family.

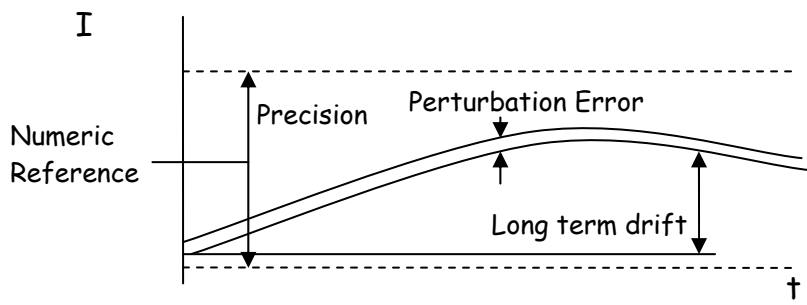


Illustration of the precision, long term drift and perturbation.