THE PULSED POWER CONVERTER AND SEPTUM MAGNET SYSTEM FOR INJECTION INTO THE ELECTRON STORAGE RING AT ESRF

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Abstract

At ESRF, the European Synchrotron Radiation Facility in Grenoble, electrons are accelerated, via a 200 MeV Linac and a 6 GeV synchrotron booster, and injected into the storage ring at 10 Hz rate. Two thin septum blade magnets and an eddy current sheet type septum magnet provide the final deflection of the injected beam. The operational requirements of the e^- injection scheme and the resulting demanding hardware specifications are recalled. The pulsed septum magnets are briefly described. The design, circuit layout and construction of the power converters are related with emphasis on innovative aspects of general interest. Results of tests during commissioning are reported.

1. INTRODUCTION

The ESRF Storage Ring (SR) [1] injectors comprise a 200 MeV Linac and a fast cycling Booster Synchrotron (BS). A repetition rate of 10 Hz keeps the beam charging times short compared with the beam lifetime. The actual parameters of the SR are summarized in Table 1.

Table 1: Parameters of the ESRF Storage Ring

Nominal beam energy (GeV)	6
Beam current (mA)	200
Number of bunches	≤ 992
H/V beam emittance (nm·rad)	4/0.04
Beam lifetime at 100 mA (h)	70
Number of straight sections	32
Radiation sources: Bendings, Undulators and Wigglers	

2. OPERATIONAL REQUIREMENTS

The ESRF complex and the SR injection layout are schematically shown in Fig.1.

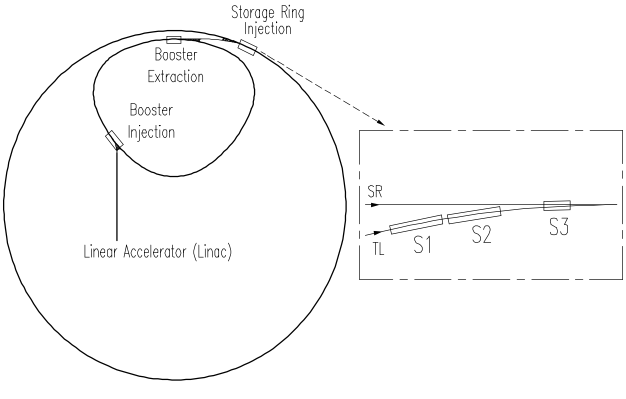

Fig.1: ESRF complex and SR injection layout.

After the Linac the electrons are one turn (1 μs) injected into the BS. Here the particle energy is increased, with a 50 ms oscillating ramp-up of magnet currents. At 6 GeV the beam is extracted from the BS and enters the transfer line (TL). Injection into the SR takes place in the horizontal plane by a combination of three thin and thick septum magnets (S1-S2 and S3) to keep the aperture needs small. These magnets produce the final deflection to align the particle trajectory to be parallel to, but displaced by about 20 mm from the circulating beam. Four fast bump magnets, arranged symmetrically around the midpoint of the SR high beta injection straight section, provide a local orbit deviation to move the stored beam close to the S3 septum. The injected particle pulse is then captured within the acceptance of the SR.

3. THE PULSED SEPTUM MAGNETS

Table 2 summarizes the characteristics of the monoturn septum magnets S1-S2 and S3, shown in Fig.2.

Table 2: Characteristics of magnets:	**S1-S2**	**S3**
Deflection angle (mrad)	44	20
Physical/magnetic length (mm)	978/950	580/500
Yoke cross section (mm^2)	120x120	80x80
Gap aperture HxV (mm)	48x13	25x10
Nominal field (T)	0.90	0.87
Nominal excitation current (kA)	9.6	8
Impedance L/R (μH/mΩ)	5/0.7	1.9/2
Integrated field (T·m)	0.88	0.44
Total septum blade thickness (*) (mm)	7	2 to 4
Lamination steel	TRANSIL 280 (3% Si)	

(*) including the magnetic screen

S1 and **S2** are two current sheet septum magnets [2], electrically connected in series. The 1 mm thick stainless steel vacuum chamber in the gap is water cooled. For a vacuum of < 10^{-8} mbar, the chamber is to be baked at ~300 °C. In doing so the septum must be disassembled and the magnet displaced horizontally. The H/V beam dimensions in the line are 18/10 mm and the sagitta is 22 mm. The yoke is composed of glued 0.35 mm sheets. The end plates and the lamination are bolted together. The magnetic screen is a 1.5 mm ARMCO sheet. The winding is water cooled (Q = 1.6 l/min., Δp = 7 bar). The r.m.s. current density in the septum is 16 A/mm^2.

S3 is an "eddy current" septum magnet [3,4,5]. So the lamination is kept out of the high quality (10^{-10} mbar) vacuum of the SR and the electrical impedance seen by a bunch of stored particles is minimized. The septum blade is part of a 10 mm thick copper shielding box which surrounds the yoke of the magnet completely and extends beyond its ends. To make the shield work effectively a short current pulse is needed. A compromise with the current supply has led to a half-sinusoidal pulse of 60 μs duration. Thereby the penetration depth in the copper is 0.7 mm. A 0.38 mm PERMALLOY magnetic screen, oven-brazed on the septum blade, reduces the leakage field at the circulating beam to 10^{-3} of the gap field. The lamination is composed of 0.2 mm sheets insulated by oxide film. The winding conductor in the gap (10x7 mm^2, hole 4 mm ∅), is water cooled. The external return conductor (4 x 30 mm^2) does not need forced cooling. The r.m.s. current in the winding is 140 A. The septum blade is cooled (Q = 2 l/min) by a separate copper pipe embedded in the thicker edges. The maximum total power dissipation is 90 W and the temperature rise is < 65 °C. The magnet tank can be moved by 6 mm to adapt the radial septum position to the SR beam emittance.

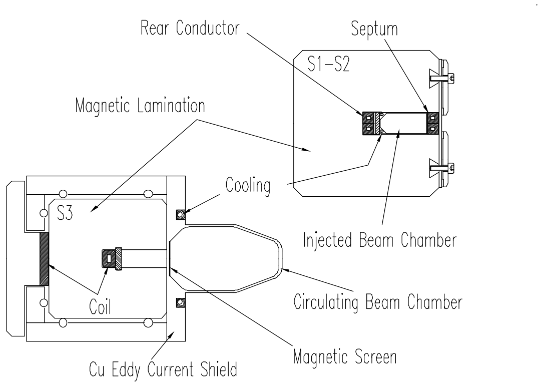

Fig.2: Cross-section of S1-S2 and S3 magnets

4. THE POWER CONVERTERS

Table 3 shows the features of this equipment, developed and built in industry to a CERN specification [6].

Table 3: Data on power converters: **S1-S2** **S3**

	S1-S2	S3
Regular pulse repetition rate (Hz)	9.5 to 10.5	
Max. charge voltage (kV)	2	
Max. charge current (A)	10	5
Energy storage capacitor (μF)	640	120
Peak/r.m.s. load current (kA)	10/1.2	8/0.14
Pulse duration (ms)	2.5	0.060
Current flat-top (μs)	60	2
Long term current flat-top stability (%)	0.1	
Load L/R (μH/mΩ)	5/2	3/5

4.1 *Mode of operation*

An electrical diagram is shown in Fig.3. The timing pulse sequence controls the capacitor charge and its discharge into the magnet: FOREWARNING pulse (FW) starts the 80 ms charge; WARNING (W) ends the 5 ms voltage stabilisation; START (ST) initiates the discharge; MEASURE (MEA) monitors the current. Time windows after each pulse lock the complete sequence. REMOTE or LOCAL actuation mode, current setting and timing is possible as well as pulsing at slower rate or in single-shot. The actuations are OFF, STAND-BY, ON and RESET. The computer control interface, is based on an RS-232 serial link. Isolation of in/out signals to the electronics and the use of optic fibers to drive the power switches provide for higher noise immunity.

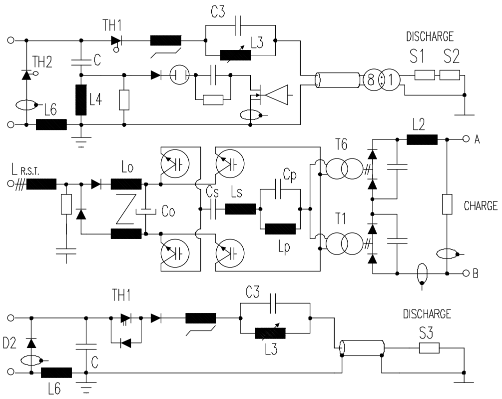

Fig.3: Electrical diagram of power converters

4.2 *Layout of power converters.*

A power converter consists of two 19″ cubicles, housing the charge circuit and the energy storage and switching section, located at ~15 m distance from the magnets.

4.2.1 *Charge circuit*

This includes an a.c. soft start and filtering section, a 6-pulse diode rectifier and a d.c. filter (L_o=5 mH, C_o=2.25 mF, f_o=47 Hz). The d.c. link (U_o=540 V) powers a double resonant d.c.-d.c. converter with four IGBTs (Insulated Gate Bipolar Transistors - 200L120 - FUJI/J) commutated at a frequency of f_p to f_s /2. The resonant circuits are for S1-S2: C_s / C_p (μF) = 120 / 0.5, L_s / L_p (μH) = 9.3 / 200 and f_s / f_p (kHz) = 75 / 16; and for S3: C_s / C_p (μF) = 120 / 0.066, L_s / L_p (μH) = 46 / 900 and f_s / f_p (kHz) = 91 / 20. Six ferrite-transformers (N_1/N_2=14/10) are connected to fast diode rectifiers with 2.1 μF capacitors on the output. The transformer primaries are in parallel and the rectifiers in series. A choke (L_2 = 10 mH) on the HV side filters the current and protects the diodes when the capacitor voltage reverses polarity.

4.2.2 *Discharge circuit of converter S1-S2*

The capacitor is discharged by a thyristor TH1 (N320CH40 - WESTCODE/GB) into the magnet via two cables in parallel and a pulse matching transformer (TRASFOR/CH) located under the magnet. The transformer characteristics are collected in Table 4.

A saturating reactor L_5 (40/5.5 μH) limits the initial di/dt of the pulse. The top of the sinusoidal current is flattened by a third harmonic parallel resonant circuit L_3-C_3 (170 μH-480 μF). Control of the magnet current during the 60 μs flat-top is performed by a dynamic filter connected across an inductance L_4 (100 µH) [7]. Its power amplifier derives a fraction of the pulse current, using MOSFET transistors (SKM 151 - SEMIKRON/D) under 200 V_{dc}. To recover the capacitor energy without affecting the pulse shape a thyristor TH2, fired ~ 3 ms after TH1, and an inductance L_6 (5 mH) are added. The duration of the ~500 A current pulse through TH2 is 6 ms. The dynamic filter and the magnet currents are monitored by transformers type 1025 and 1423 (PEARSON/US).

Table 4: Characteristics of pulse transformer

Number of columns	3
Iron cross-section (cm^2)	776
Weight (kp)	890
Dimensions HxDxW (mm)	650x600x580
Air gap (mm)	2.4
Number of turns N1:N2	16:2
Design $\int$ u dt (V s), without d.c. core bias	1.5
Winding resistance referred to primary (mΩ)	4.7
L_σ/L_μ ref. to primary (µH/mH)	10/20
Core lamination	M6T35
Winding insulation class	H

4.2.3 ***Discharge circuit of converter S3***

S3 has no matching transformer and TH1 must handle the full current (8 kA, 60 µs). An SCR switch would suffer from excessive current density in the vicinity of its auxiliary turn-on thyristor before the plasma spreads out. Hence a GTO (Gate Turn Off) thyristor is used in stead (DG758 AX - GEC/GB). Due to the fine inter-digitation of the gate-cathode electrodes, all the silicon surface comes on at once and allows much higher initial di/dt. The GTO assembly includes an antiparallel and a series protection diode. A third harmonic pulse shaping circuit L_3-C_3 (0.7 µH-100 µF) is present without dynamic filter. The saturating reactor L_5 (5/0.1 µH) consists of a simple C-core. The energy recovery path includes a diode D_2 and the inductance L_6 (1 mH), selected >> L_{load} to keep the pulse duration unchanged. The pulse transmission line is made of three parallel coaxial cables.

4.2.4 ***Electronics of S1-S2***

The charge voltage set point is proportional to the magnet current reference. After squaring, this signal is integrated during the pulse to obtain the energy deposited into the magnet. To model its thermal behaviour cooling between pulses is simulated by a suitable discharge time constant of the integrator. The resulting signal tunes the capacitor voltage when the magnet heats up. The charge current I and voltage V are regulated by three parallel loops so as to limit the current below a preset value, to maintain constant power (V·I) during charge and to perform the fine voltage stabilisation. The power reference is derived from the capacitor energy at FW and W assuming constant charge time T_c: $(V \cdot I)_{reference} = (V_{reference}{}^2 - V_{recovery}{}^2) \cdot C / (2 \cdot T_c)$.

5. TEST RESULTS

At the factory, after HV insulation tests, the charge circuits have been run at 2 kV, 4 A d.c. on a resistive load. Some wave-shapes, recorded during pulsed operation, are shown in Fig 4.

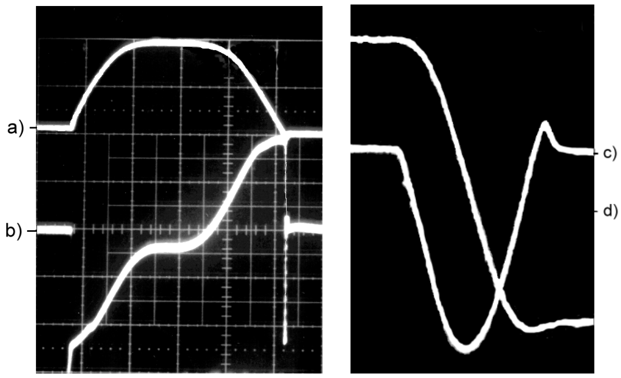

Fig 4: Wave shapes recorded during tests: **S1-S2** at 9 kA: a) Magnet current (5 kA/d-0.5 ms/d); b) Transformer primary voltage (0.8 kV/d). **S3** at 8 kA: c) Magnet current (2 kA/d-20 µs/d); d) Capacitor voltage (0.5 kV/d)

6. CONCLUSIONS

The requirements of the SR injection system have been satisfied by two types of pulsed septum magnets designed and assembled at CERN. The power converters, operating at 10 Hz, perform charge at constant power and pulse current flat-top regulation via a parallel dynamic filter. A GTO switch for S3 and a particularly reliable timing system characterize the equipment. The double-resonant soft-switched-mode charge circuit permits the fast pulse repetition rate and avoids mains reactive power and current harmonics typical of a.c. thyristor controllers. Its characteristics of current source make the charger short-circuit proof and therefore very robust and reliable. So far operational records of this equipment at ESRF have been excellent.

7. REFERENCES

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[6] Technical specification for the pulsed power supplies of the septum magnets S1-S2, Feb. 1990. F.Völker.

[7] The capacitor discharge power converters for the pulsed septum magnets in the PS straight sections 16 and 58, CERN/PS/88-26 (PO). F.Völker et al.