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THE INJECTION KICKER SYSTEM OF THE CERN ANTIPROTON ACCUMULATOR

D. Fiander, K. Metzmacher, S. Milner, P. Pearce, A. Poncet, J.C. Schnuriger, T. Wikberg.
CERN, Geneva, Switzerland.

Summary

The antiprotons produced at the target are deflected onto the injection orbit by a kicker magnet. The beam emittance demands a very large kicker aperture and bunch interval imposes a short fall-time of the field pulse. A movable fast shutter shields the stack space from pulsed stray field and permits a free passage from injection to stack orbit within each injection cycle. The ferrite delay-line kicker, the servo-driven shutter and the ultra high vacuum (UHV) tanks are described. Pulsed magnetic field measurements and operating experience with this kicker system are also reported.

Introduction

In each injection cycle, the $\bar{p}$ produced at the target are transferred to the accumulator, pass through the septum magnets and are put on injection orbit without betatron coherent oscillations by a fast kicker magnet. Prior to the next injection the beam has its momentum spread reduced by pre-cooling and is then decelerated towards the already stacked beam. As the stack must not be disturbed by this repetitive process the kicker is located in the lattice where αp is large, so that with slightly lower momentum the stack is well separated from the injection orbit. Nevertheless, as the kicker stray field could impair performance towards the end of filling, a movable eddy current shutter shields the stack region when the kicker is pulsed.

The very large emittance of the injected $\bar{p}$ beam demands an unusually large kicker aperture height, varying according to the local β_V, and similarly large useful field region width varying with β_H. The separation between the injected beam trajectory and the injection orbit at the septum determines the nominal deflection angle and hence kick strength (Table 1). The 105 ns bunch interval of the incident target beam is maintained between produced $\bar{p}$ bunches, requiring a short fall-time of the kicker field. The total magnetic length needed is determined by the kick strength, vertical magnet aperture and available pulse current; Fig. 1 shows that the length has to be split between two locations, upstream and downstream of a lattice focussing quadrupole.

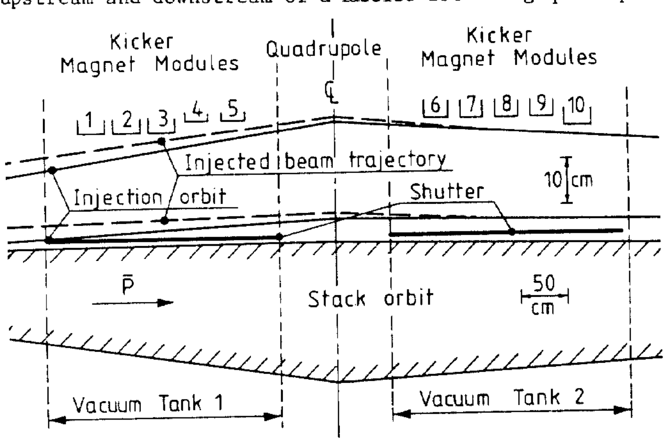

Fig. 1. Beam trajectories in injection kicker region.

Besides the previous requirements other constraints such as high voltage withstand, UHV performance, bake-out capability, field reversal and limited access for maintenance lead to the solutions described.

General Concepts

There are four design options which must be taken:

i) Kicker located inside or outside the vacuum
ii) C-core or window frame ferrite circuit

Table 1. Performance Specification

Beam deflection angle (3,5 GeV/c)	7.37	mrad
Corresponding kick strength	880	G m
Stray/main field ratio	$< 2.0 \times 10^{-3}$	
Available vacuum tank length	2 x 2.5	m
Aperture (width x height)	251 x 88 or 226 x 100	mm^2
Field rise/fall-times (5-95)%	≤ 90	ns
Pulse length	≥ 500	ns
Repetition rate	$\cong 0.5$	Hz
Vacuum	$\leq 10^{-10}$	Torr

iii) Delay-line or lumped inductance magnet
iv) Pulse generator impedance and voltage levels, with consequent influence on magnet design and space needed.

The design of the accumulator and the nature of its stacking process determine the options in the following way. There is no alternative to placing the magnet within the vacuum envelope; outside would imply an impossibly large ceramic vacuum chamber and stray field screening would be inadequate. The C-core circuit is chosen because the beam has to be decelerated from injection to stack orbit, necessitating an obstruction-free aperture. A delay-line magnet is preferred to meet the magnetic pulse response specification and to avoid reflections in a thyratron-switched pulse generator. The generator impedance and voltage are determined by adopting an existing 15 Ω 80 kV design of proven reliability and in widespread use on other kicker installations[1].

With aperture, rise-time and voltage fixed the deflecting strength of a magnet is also fixed and the total required strength can be obtained only by using a number of separately excited magnet modules. Ten are needed for the injection kicker, providing about 25% reserve strength.

Choosing the magnet environment and type crystallizes the main problems to be solved. These are compatibility of large ferrite-cored devices with a bakeable UHV system and ability to screen the stack region from the kicker field.

Design and Construction

Two large vacuum tanks, each housing five magnet modules, are required. Both tanks also contain fixed screens and movable shutter blades to limit stray field in the stack region (Fig. 2). The module is a delay-line device matched to its dedicated generator and terminated in its characteristic impedance. The cable delay-line generator has double-ended switching, with consequent pulse length control. All generators, terminators and shutter servo drives are installed inside the accumulator building and are inaccessible during machine operation. Computer control is effected via local CAMAC interfaces.

The design pressure of the accumulator calls for specific outgassing rates of $< 1 \times 10^{-12}$ Torr $\ell/(s\ cm^2)$ for all construction materials exposed to vacuum. This requirement can be met only if the entire vacuum system, including the injection kicker tanks, is bakeable to 300 °C for periods of 48 hours or more. Low specific outgassing rates can be obtained by careful pre-firing of the components; for example the fully machined ferrites are baked to 950 °C at 10^{-5} Torr and alumina ceramics air fired to 1000 °C. Despite their size the premachined stainless vacuum tanks are stress relieved and degassed at 950 °C and 10^{-5} Torr, a procedure applied where possible to all other components for inclusion in the tanks.

Magnet Module

The design stems from computer predictions of electrical and magnetic behaviour based on the estimated equivalent circuit. The module (Fig. 3) is an L-C ladder

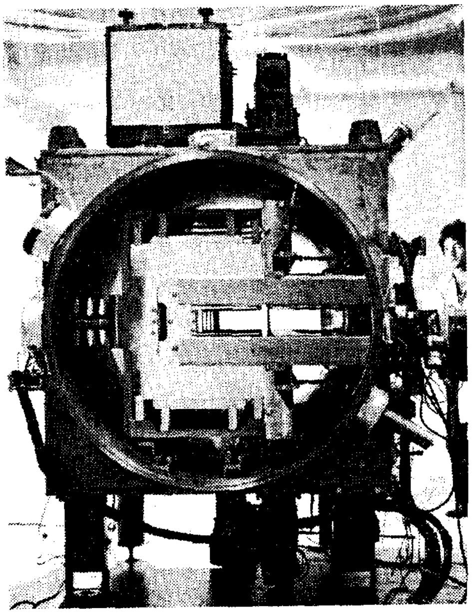

Fig. 2. End view of kicker assembly.

network of either 10 or 12 cells depending on the aperture dimensions. Each cell comprises a three block ferrite C-core, loosely sandwiched by AℓMg3 alloy plates which are high voltage (HV) pulsed and interleaved with similar plates held at earth (E) potential. Cell inductance is that of the ferrite bounded aperture and cell capacitance that between HV and E plates. The design characteristic impedance is obtained by correctly dimensioning the capacitor plate system.

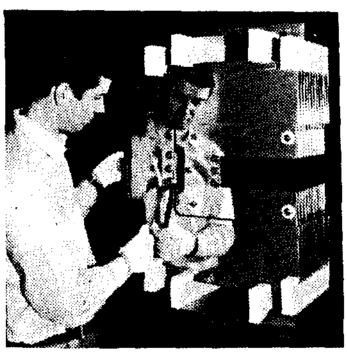

Fig. 3. Magnet module during final assembly.

The module is a single turn device; its HV stainless conductor is located inside the C-core aperture and is connected to all HV capacitor plates via Inconel spacers and stainless tie rods. This material choice minimises differential expansion during bakeout. The E conductor, which is similarly joined to all E plates, is placed behind the ferrite backleg contrary to usual kicker practice. This position is chosen to minimise the distance between the useful field region of the aperture and the stack orbit, leaving it free for the fixed screen and moving shutter; the penalty is some small inductance increase.

Both extremities of the module conductors are connected by matched strip lines to coaxial feed-throughs in the tank wall. Thus field polarity can be determined by appropriate connection of generator and terminator.

Vacuum Tank, Screens and Shutter

Each vacuum tank has a nominal diameter of 1.1 m and length of 2.5 m and is equipped with WHEELER* type end flanges, implying tolerances of 0.1 mm on relatively flexible structures. The stack region is separated from the rest of the tank by two full length vertical fixed stainless screens and two full length opposed-motion 10 mm thick titanium shutters blades, anchored to the tank wall with titanium alloy flexible parallel strip pivots. These ensure frictionless parallel translation of the shutter movement with low dynamic outgassing rates. They accommodate differential expansion between tank and shutter during bakeout.

Stack region stray field is minimised by RF contacts between fixed screens and tank and low clearance between shutters and screens (< 1.5 mm). Additional horizontal screening plates are located above and below the stack orbit; these are enlarged at the tank extremities to reduce the stray field of the end magnets.

Shutter Drive

Each shutter blade is driven from an externally mounted dc servo motor, the rotary motion of which is transformed into linear motion by two crank mechanisms, one at each end of the tank. The blade is actuated by two long push rods attached to the cranks and vacuum sealed by fast acting high performance bellows. These have a diameter of 50 mm and length of 120 mm, are plasma welded from 0.13 mm thick special stainless sheet and cope with a shutter stroke of 60 mm. They are one of the critical elements in the shutter drive, of which Fig. 4 is a schematic.

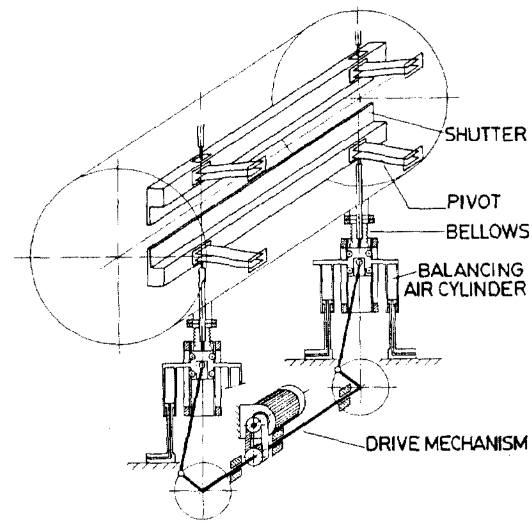

Fig. 4. Mechanical drive of shutter

The shutter drive control system allows the dwell in closed or open positions to be adjusted to meet machine requirements.

Performance

Magnets

Low Voltage (LV) Measurements. Pulse propagation and magnetic field response are measured with an excitation of ≃ 0.2A. Inductance distribution is evaluated from individual cell voltages and magnetic rise-time and strength from the difference voltage between first and last HV plates. Fig. 5 shows a typical difference voltage waveform and its evaluation. Good agreement is obtained both with computer predictions and complementary strip-line probe measurements, the latter also confirming absolute deflection strength.

The $\int B d\ell$ distribution across the horizontal median plane of a module outside its tank, with simulated screen and shutter, is measured with strip-line probes but using RF excitation. Open and closed shutter measurements, plotted in Fig. 6 are within ±1.5% of prediction in the useful aperture. This error can be attributed to omission of end and eddy current effects from the computer model.

LV measurements permit valid prediction of HV performance because the reluctance is mainly determined by

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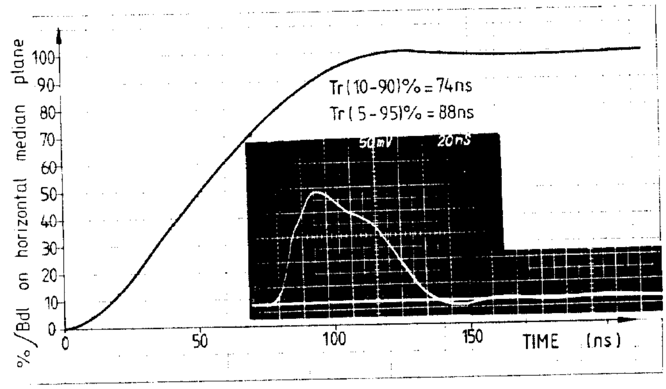


Fig. 5. Magnetic field rise (fall is similar).

the large core air-gap and the ferrite is kept below saturation at full HV excitation.

High Voltage (HV) Measurements. This is a two-stage evaluation. Firstly, each module is pulse conditioned to the desired 40 kV pulse voltage (≃ 2600 A). Absolute deflection strength, field rise and fall-time and flat top ripple are then measured by strip-line probe (w = 4 mm, ℓ = 600 mm). Secondly, five modules assembled in their tank are excited at 2600 A from a test generator system. Two probes are installed, one in the aperture (w = 4 mm, ℓ = 2500 mm) and one in the stack region (w = 28 mm, ℓ = 2500 mm). The five modules can be pulsed in various combinations and the ∫Bdℓ of stray and main field can be simultaneously measured for both shutter positions (Fig. 6. and Table 2.). The contribution of a module to the total stray field depends strongly on its position in the tank. Initially end modules contributed ten times the stray field of the

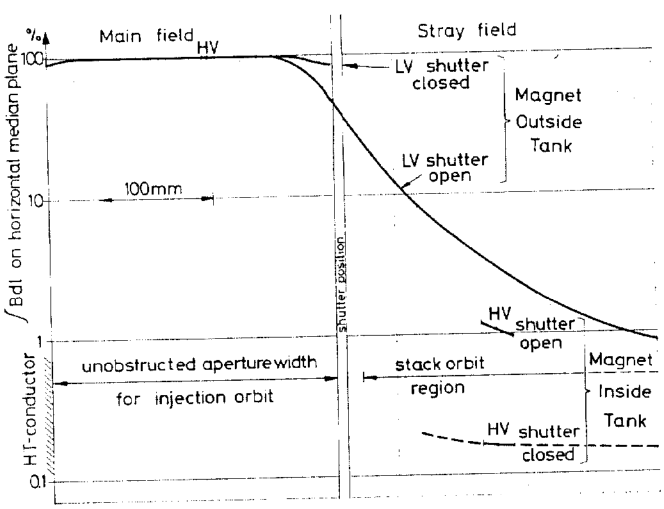


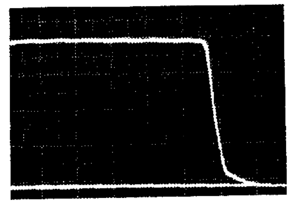
Fig. 6. Main and Stray ∫Bdℓ distribution.

Table 2. Generator and magnet performance

Pulse generator charging voltage (max.)	80	kV
Impedance	15	Ω
Current rise (fall) (10-90)%	28	ns
Thyratron switch type (EEV)	CX 1171	
Jitter (absolute)	< 5	ns
Pulse length (variable)	100 - 750	ns
Magnet module kick strength (max.)	114 or 119	G m
∫Bdℓ rise (fall) (10/90)%	74	ns
(5/95)%	88	ns
Ferrite mass/module (Philips 8C11)	≃ 55	kg
Module total mass	≃ 280	kg
System kick strength (max.)	1160	G m
System kick jitter (absolute)	< 2	ns

central module, later reduced to six times by additional horizontal screening. The overall stray to main field ratio 150 mm behind a closed shutter is < 1.6×10^{-3}.

The main ∫Bdℓ of three modules excited from three synchronised pulse generators is shown in Fig. 7a, where the residual tail, not present in the final installation, is due to excessive delay cable length of the generators. Fig. 7b depicts the stray ∫Bdℓ of one module only.



200 ns/ div

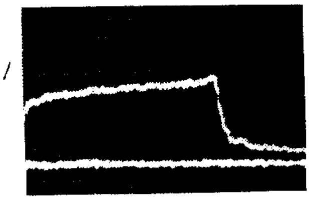
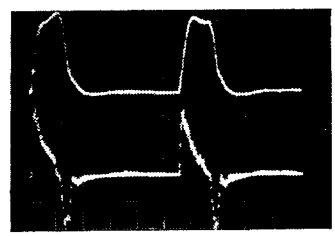


Fig. 7a. Typical main ∫Bdℓ. Fig. 7b. Typical stray ∫Bdℓ

Shutter

Mechanical stresses are limited by keeping acceleration below 4 'g' by appropriate choice of servo drive function. The time needed to clear or close an aperture half height of 50 mm is ≃ 100 ms. Fig. 8 shows typical motor speed and torque waveforms of opening and closing strokes; the good symmetry between strokes is obtained by correct pneumatic balancing of shutter weight.



angular velocity 100 rpm/div

torque 20 Nm/div

100 ms/div

Fig. 8. Motor angular velocity and torque.

Shutter servo drive assemblies withstand life tests of 10^7 cycles without failure.

Vacuum

For vacuum acceptance each module is vacuum baked at 300 °C during 24 h. The residual pressure after cool-down is ≃ 10^{-11} Torr, the pumping speed being 2000 ℓ/s. The pressure in the injection kicker tanks in the accumulator is ≃ 10^{-10} Torr after a 150 °C/24 h bakeout; the pumping speed per tank is 10000 ℓ/s, due mainly to titanium sublimation pumps. The dynamic gas load of the moving shutter is negligible.

Operating Experience

The injection kicker system has operated for 2000 h since commissioning in June 1980; no conceptional or constructional weaknesses are apparent and reliability is high. The system is used both for infrequent injection of p bunches for accumulator studies and for its more onerous design role of repetitive $\bar{p}$ injection. Computer controls allow easy adjustment of kick strength and synchronisation with the beam; inter-module synchronisation is well maintained by hard wired electronics and can be verified in the control room by analogue signal monitoring.

The shutters, although not always used, function correctly when required. The flexibility of their control system is apparent by the ease with which the operating cycle can be changed. All parts of the mechanical drive and the vacuum bellows have operated faultlessly.

Reference

1. FIANDER, D., Hardware for a full aperture kicker system for the CPS, Proc. of 1971 Particle Accelerator Conference, p. 1022.