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ON THE DESIGN OF FAST KICKERS FOR THE ISABELLE BEAM ABORT SYSTEM*

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Abstract

The ISA beam abort (extraction) system must be highly efficient, in the sense of producing minimum beam loss, and reliable to prevent serious damage to accelerator components by the circulating high-energy beams. Since the stored beams will be debunched, the low-loss requirement can be met only with ultra-thin extraction septa and/or fast-acting kickers.

This paper examines the design of the ISA extraction kickers subject to a set of extraction channel constraints and a given maximum working voltage. Expressions are derived for determining system parameters for both a lumped parameter magnet and a delay-line magnet. Using these relationships, design parameters are worked out for several possible system configurations. The paper also describes the construction of a full-scale prototype module of the kicker and summarizes the preliminary test results obtained with the module.

Introduction

The proposed primary beam-abort system for each ring of the ISA will consist primarily of a fast kicker and a series of pulsed magnetic septa of progressively increasing thicknesses. The beam will be ejected vertically downward towards an underground beam dump in the 6 o'clock area of the accelerator.[1]

The septum magnets will be energized with "slow" half-sine current pulses and the kicker magnets with "fast" rectangular pulses. Since the stored circulating beam will be debunched, particles will be lost on the first septum during normal operation of the abort system. This loss and the resulting heating of various down-stream components of the accelerator will be minimized by reducing both the thickness of the first septum and the rise-time of the kicker field-strength.

Although the kicker excitation pulse must be nominally rectangular in shape, the acceptance of the extraction channel permits some initial overshoot and ripple on the flat-top of the pulse. The amplitude of the ripple must be, however, limited to less than ± 2% near the end of the pulse to properly eject the so-called "whipping tail" of the beam.

The kicker excitation pulse will be generated by a lumped parameter PFN as shown in Fig. 1. The PFN will be equiped with a front speed-up cell of the same design as that used by Faugeras.[2] The pulse generator will contain a crowbar circuit to prevent pulsing the magnet in case of a pre-fire of the main switch. It will be located approximately 40 m away from the magnet outside of the machine tunnel and will be connected by means of HV pulse transmission cables.

The magnet will be a single-turn window-frame structure with a high frequency ferrite core. It will be constructed around a ceramic vacuum chamber and operated in air. The chamber will be coated with a thin metallic layer to prevent a build-up of electrostatic charge in its walls. Screens will be provided to control the magnitude of the beam coupling impedance of the magnet structure.

For practical reasons, the maximum operating voltage will be limited to 60 kV. This will necessitate dividing the magnet into sections in order to meet the required rise-time of the field. Magnet sections may have to be further sub-divided and interconnected with capacitors to minimize cable reflections. Since the abort system must track the energy of the circulating beam, the operating voltage of the pulse generator will vary over a range of 13:1.

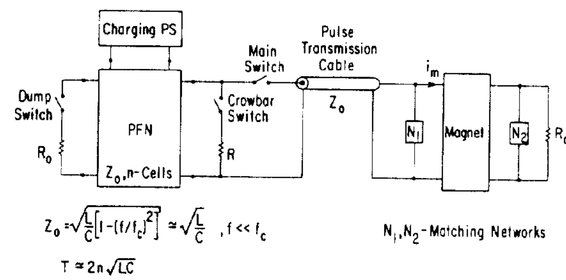

Fig. 1. Block diagram of kicker system.

In the pulse generator(s), the main high-current switches will be either deuterium thyratrons or spark gaps. If thyratrons are used, the peak current per device will have to be limited to about 10 kA.** With spark gaps on the other hand there is little known experience of operation over wide range of voltages. The system will be pulsed at a rate of one pulse every 10-20s during the initial testing phase of the accelerator; during normal operation of the machine the rate will be once or twice per day. The total number of shots in 10 years of operation is expected to be in the order of 10^5.

This paper examines the design of the beam abort kicker for a given set of extraction channel constraints. Design parameters are worked out for several possible configurations of the system assuming a maximum working voltage of 60 kV. The design of a full-scale prototype module is described and preliminary test results summarized. Transient responses of networks have been computed with IBM ECAP computer program.

System Parameters

The pertinent basic parameters of the ISA beam abort system are given in Table 1. The quoted beam loss fraction and d_{s1} correspond to a 0.25 mm thick first septum (Al or Ti). As is well known, for a window-frame magnet

$$\text{Inductance } L/\ell = \frac{w}{g}\mu_o \text{Henrys/meter} \qquad (1)$$

$$\text{and Current } I = \frac{Bg}{\mu_o} \text{ Amperes,} \qquad (2)$$

where B is in Teslas, w and g in meters, and $\mu_o = 0.4 \times 10^{-6}$ H/m. Since the displacement of the beam at the septum is proportional to B, the rise-time of the field $t_{rB} = t_{rd}$. Also, since

$$I = \frac{Bg}{\mu_o} = \frac{pg\theta}{0.3\ell\mu_o} \qquad (3)$$

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**Based on reported experience with state of the art thyratrons at CERN.

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Table 1. Parameters of the ISA Beam-Abort System.

p (GeV/c)	θ (10^{-3} rad)	$B\ell = \frac{p\theta}{0.03}$ (kG.m)	w (m)	g (m)	ℓ (m)	D (mm)	d_{s1} (mm/us)	t_{rd} (us)	Beam Loss Frac.	τ_{br} (us)
30-400	0.68	0.7-9.1	0.06	0.06	6.0	37	111	0.333	0.3x10	12.8

where: p = momentum, θ = defl. angle, w = kicker mag. gap width, g = gap height, ℓ = magnet length, D_{s1} = max. beam displacement at first septum, d_{s1} = ave. rate of beam displacement, t_{rd} = displacement time, τ_{br} = beam revolution time.

for θ = constant, $I \propto p$.

For the system of Fig. 1 with PFN impedance Z_o and termination $R_o = Z_o$, $\omega \ll \omega_c$ (cut-off frequency of the PFN) the charging voltage is

$$V = 2IZ_o. \tag{4}$$

If the maximum specified working voltage is V_{max}, then

$$Z_{o\,max} = \frac{V_{max}}{2I} \tag{5}$$

Recognizing the fact that system impedance depends in a discrete way on the impedance of the available cable Z_c,

$$Z_o = \frac{Z_c}{m},\ m = 1,2,\ldots < Z_{o\,max} \tag{6}$$

where m = number of cables in parallel.

Lumped Parameter Magnet

Consider the case where in the system of Fig. 1 the magnet can be represented by a lumped inductance L and for the moment neglect the effect of the transmission cable. This representation is valid if the propagation delay or the "filling-time", τ_f, of the magnet is short relative to the rise-time of the PFN output current, t_{rI}.* For this case,

$$t_{rB} \simeq t_{rI}. \tag{7}$$

We will define the rise-time of the current as

$$t_{rI} = k\tau_L, \tag{8}$$

where $\tau_L = L/2Z_o$, and k is a system constant whose value depends on the dynamics of the PFN and on the amplitude levels between which the rise-time is measured. If the PFN were ideal (i.e. rectangular output pulse into a matched resistive load), the leading edge of the magnet current pulse would be exponential with a rather long 0-98% rise-time (k = 3.98). In this case significant improvement in rise-time could be achieved by placing a speed-up capacitor across R_o, though at the expense of some overshoot. It can be shown that with a 7% overshoot the rise-time could be improved by almost a factor of two (k = 2.1).[3]

From Eq. (8), with all quantities except L specified, the maximum load inductance $L = L_N$ which can be driven by the PFN can be determined. If this value is smaller than that of the overall magnet, L_m, the latter must be divided into, say, N sections each of length ℓ_N so that the inductance per section is $\leqslant L_N$.

Assuming that the stray inductance of connections etc. per section is L_s, it can be easily shown that

$$N \geqslant \frac{2Z_o t_{rI}}{k} - L_s,\quad N = \text{integer} \tag{9}$$

where Z_o is given by (6). Alternatively,

$$N \geqslant \frac{L_m}{2Z_o t_{rI}/k - L_s}. \tag{10}$$

Delay-Line Magnet

Consider again the circuit of Fig. 1 where the magnet is in the form of a lumped parameter delay-line. If the stray inductance of the switch and connections is L_s, the rise-time of the field in the magnet gap is

$$t_{rB} = t_{rI} + \tau_f, \tag{11}$$

where $t_{rI} = kL_s/2Z_o$ and $\tau_f = L_m/Z_o$. If the required field rise-time is smaller than that given by (11), the magnet must be again divided into, say, M sections where

$$M \geqslant \frac{2L_m/k}{2Z_o t_{rB}/k - L_s} \tag{12}$$

Note that for k = 2.0, M = N.

The Pulse-Forming Network

Consider a PFN formed by cascading n elementary T or π sections, each having a series inductance L and a shunt capacitance C. For this type of network, the characteristic impedance and pulse width are given by

$$Z_o = \sqrt{L/C} \tag{13}$$

$$T \simeq 2n\sqrt{LC}, \tag{14}$$

respectively.[4] For a given set of Z_o, T and n, the values of network elements can be determined from Eqs. (13) and (14).

A typical response of such a network terminated in R_o is shown in Fig. 2(a). This figure also illustrates the effect of the front speed-up cell (FC) and of the speed-up capacitor C_s on the shape of the output current pulse. With the FC, the front part of the pulse can be made to approach an ideal step function (b). Adding an inductance in series with

*Magnet filling-time is the rise-time of $\int B.d\ell$.

Table 2. Kicker design parameters.

Z_o (ohm)	I (kA)	V (kV)	N	N_{ct}	N_G	Z_{pfn} (ohm)	nC (uF)	I_{sw} (kA)	L (uH)	C (uF)
					10	3.35	2.09	7.2	2.36	0.21
3.35	0.5-7.2	3.6-48.2	10	40	5	1.675	6.18	14.4	1.18	0.42
					2	0.670	10.45	36.0	0.48	1.04
					1	0.335	20.90	72.0	0.24	2.09

where: N_G = number of pulse generators/system, N_{CT} = total number of cables, I_{sw} = peak current in the main switch, L and C = inductance and capacitance/PFN cell, respectively.

R_o slows down the leading edge of the pulse as expected (c), while an addition of the speed-up capacitor across R_o shortens the rise-time but produces some overshoot (d). Waveforms (a),(c) and (d) have the same initial slope (e).

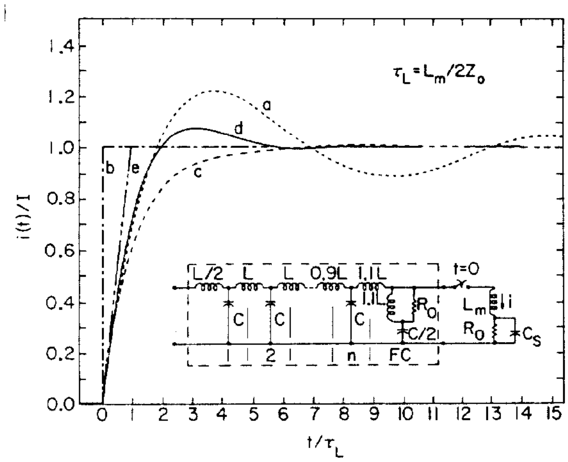

Fig. 2. Computed PFN output current pulse shapes.

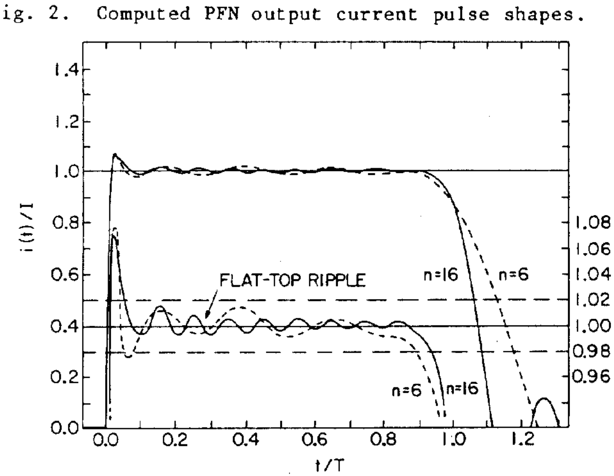

Fig. 3. Response of a PFN with front-cell for different values of n.

Varying the number of sections in the PFN with a FC driving an inductive load has little effect on the amplitude of the pulse flat-top ripple. This is illustrated in Fig. 3 for n = 16 and n = 6. The FC in effect decouples the PFN from the load and permits a more economical design.

Effect of the Transmission Cable

In an ideal case, the introduction of a lossless cable between the pulse generator and the magnet would have no effect on the shape of the pulse. Though mismatched at the load end, the cable is relatively well matched at the sending end by the resistor in the front-cell of the PFN. In practice, the stray inductance associated with the switch will given rise to reflections of the pulse at the sending end of the cable as well. With real lossy cables, the leading edge of the pulse will be distorted due to the skin effect in cable conductors.[5]

Design of the ISA Extraction Kicker

Design parameters for several possible configurations of the extraction kicker are summarized in Table 2. These are based on the following specifications and assumptions:

Given: $t_r \leqslant 0.333$ us, T = 14 us, L_m = 7.5 uH

Assumed: $V_{max} \leqslant 60$ kV, $L_s \leqslant 0.3$ uH, Z_c = 13.4ohm
k = 2.1, n = 10 cells, m = 4 cables.

For the case N_G = 1, PFN realization would require capacitors with extremely low stray inductance and utilization of strip-line construction techniques.

Prototype Module and Test Results

A prototype module of the kicker has been constructed at BNL and tested. The module consists of a 3.35 ohm 32-cell PFN, a main switch, charging power supply and a lm long magnet. The power supply and PFN capacitors are rated at 50 kV. The switch is a double-ended deuterium thyratron, EEV Type CX1171B, and the ferrite is CMI CMD5005 with $B_{max} \simeq$ 3kG. The PFN and the switch-tube are housed in separate tanks and the switch is immersed in oil. The cable is made-up of four 13.4 ohm cables in parallel (Belden No. YR-10914) and the terminating resistor is a parallel combination of four 14 ohm Carborundum Type AS power resistors.

So far the system has been pulsed only several hundred times up to 6 kA and has not been fully optimized for rise-time and overshoot. Measured rise-time of the integrated field is 0.4 us, overshoot is less than 10% and pulse-top ripple about $\pm$ 3%.

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