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THE INJECTION BUMPER SYSTEM FOR LEIR

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To satisfy the ion beam luminosity requirements for CERN's future Large Hadron Collider (LHC), a small accumulator, the Low Energy Ion Ring (LEIR), is being built in the injector chain of accelerators. LEIR will use a combined longitudinal and transverse multi-turn injection scheme which requires a bumper system comprising four individually pulsed dipole magnets. The paper discusses the bumper system, in particular the power supplies which will produce a pulsed current linearly decreasing from 1.2kA to zero in a time variable between 120µs and 300µs. Each power supply employs a primary discharge circuit, comprising a storage capacitor, an IGBT switch and the magnet load inductance, to establish the peak current, and a free-wheel circuit in parallel with the magnet, comprising a diode and capacitor, to produce the linear current slope. A novel feature of the circuit is the use of a variable bias voltage on the free-wheel capacitor, allowing continuous variation of the slope duration.

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Abstract

To satisfy the ion beam luminosity requirements for CERN's future Large Hadron Collider (LHC), a small accumulator, the Low Energy Ion Ring (LEIR), is being built in the injector chain of accelerators. LEIR will use a combined longitudinal and transverse multi-turn injection scheme that requires a bumper system comprising four individually pulsed dipole magnets.

The paper discusses the bumper system, in particular the power supplies that will produce a pulsed current linearly decreasing from 1.2 kA to zero in a time variable between 120 µs and 300 µs. Each power supply employs a primary discharge circuit, comprising a storage capacitor, an IGBT switch and the magnet load inductance, to establish the peak current, and a free-wheel circuit in parallel with the magnet, comprising a diode and capacitor, to produce the linear current slope. A novel feature of the circuit is the use of a variable bias voltage on the free-wheel capacitor, allowing continuous variation of the slope duration.

I. INTRODUCTION

The multi-turn injection scheme requires a symmetrical arrangement of four bumper magnets centred on a septum magnet as shown in Fig. 1.

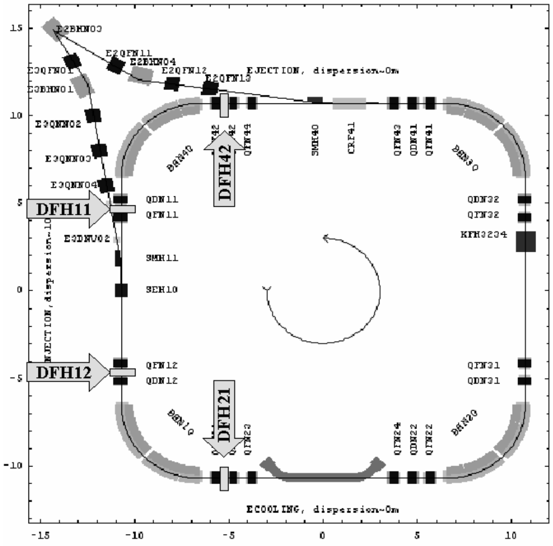

Figure 1. Layout of the LEIR machine showing the four bumper positions DFH11, DFH12, DFH21 and DFH42.

Bumpers DFH42 and DFH21 require similar amplitude magnetic fields, as do bumpers DFH11 and DFH12. The required peak ∫Bdl per bumper of 120 G.m corresponds to a peak magnet current of 1.2 kA. Each magnet represents an inductive load of approximately 14 µH. Their physical and mechanical characteristics are described in [1]. Four individual pulsed power supplies will excite the four bumpers. The rise-time of the magnetic field is not critical provided it is long compared to a betatron oscillation period (~ 1 µs) and short compared to the 200 ms period of the injector linac cycle. The decreasing injection ramp will be variable between 120 µs and 300 µs, with a nominal value of 210 µs. The required linearity of the injection ramp is ± 2 % and the tracking between the normalized amplitudes of the four individual magnet currents should be ± 1 % or better. Compensation for the finite particle flight time between the four bumpers will be achieved by differential timing of the four pulsed power supplies. The LEIR machine will cycle every 3.6 s during which a burst of maximum eight pulses at 5 Hz repetition rate is required for injection.

II. DESIGN PROPOSAL

A. Basic principle of circuit operation

Fig. 2 shows a simplified electrical circuit for the proposed bumper magnet power supply. A primary capacitor, Cp, is pre-charged to a voltage Vp.

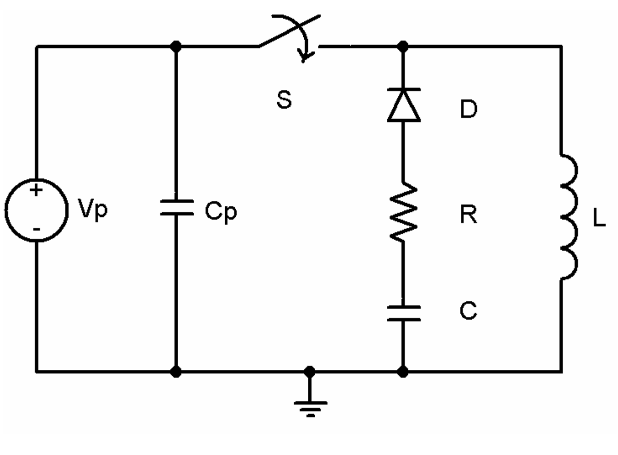

Figure 2. Simplified electrical circuit of one injection bumper power supply.

On closing switch S a resonance is excited between Cp and the load inductance L and a sinusoidal rising current is established in the circuit. Once the required peak current amplitude is attained the resonant discharge is interrupted by opening switch S at which point the current in the free-wheel circuit comprising diode D, resistor R, and capacitor C begins to flow; the circuit still being a resonant one but whose frequency is now determined primarily by L, C, and R.

Suitable choice of component values C and R produces a load current which decreases quasi-linearly from its peak value to zero over a predetermined duration, at the end of which the current is interrupted at the zero crossing due to the presence of the diode D. Capacitor C is charged negatively during this period to a voltage proportional to the integral of the load current over the slope duration.

Fig. 3 below shows representative current waveforms from a PSpice™ simulation output for a 210 µs injection slope. The first trace shows the current through switch S increasing to the required peak current in the load inductance at which point switch S opened. At this instant the voltage at the junction of switch S and D rapidly becomes negative due to the change in dI/dt in L. The second trace shows the freewheel diode circuit beginning to conduct at the instance of switch S opening; D changing from being reverse-biased to forward-biased.

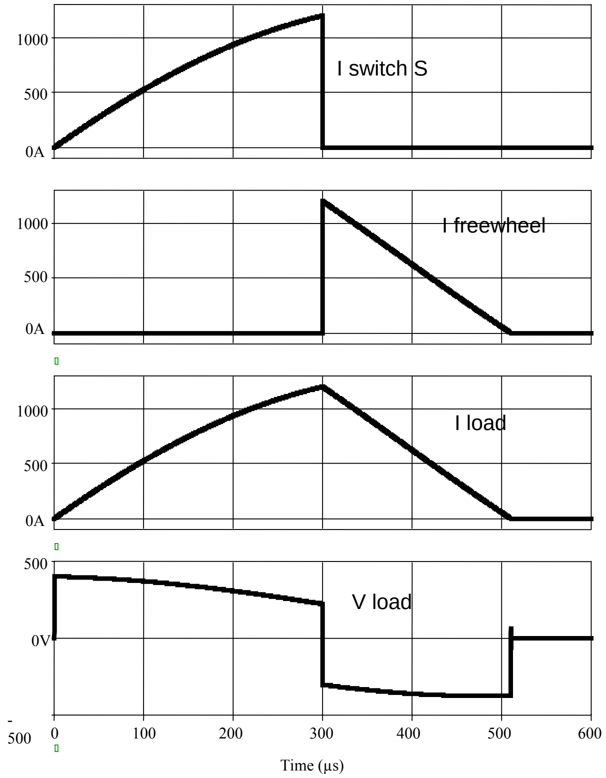

Figure 3. Simulated current and voltage waveforms in the primary freewheel and load branches of the circuit.

The third trace shows the current in the load inductance, L, which is simply the sum of the currents in the upper two traces. The last trace shows the voltage at the junction of switch S, diode D and the load inductance L.

B. *Injection slope linearity*

Mathcad™ calculations show that the peak deviation from an ideal slope of approximately ± 1.5 % can be achieved over the whole range of requested slope lengths. It is assumed that the best fit of the actual slope to an ideal slope is one which crosses the latter at $t=0$, $t=T_s/2$ and $t=T_s$, where T_s is the required slope length. Fig. 4 shows the result of one such calculation to determine the best linearity achievable for the required nominal slope length of 210 µs.

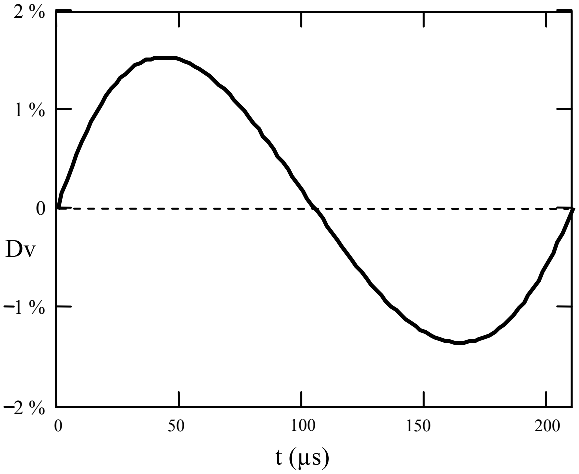

Figure 4. Percentage deviation, Dv, of the actual current from an ideal slope for the nominal duration of 210 µs.

C. *Injection slope length adjustment*

1) *Variation of the value of capacitor C*

A continuous set of values of L, C and R can produce a particular slope length within the linearity constraints.

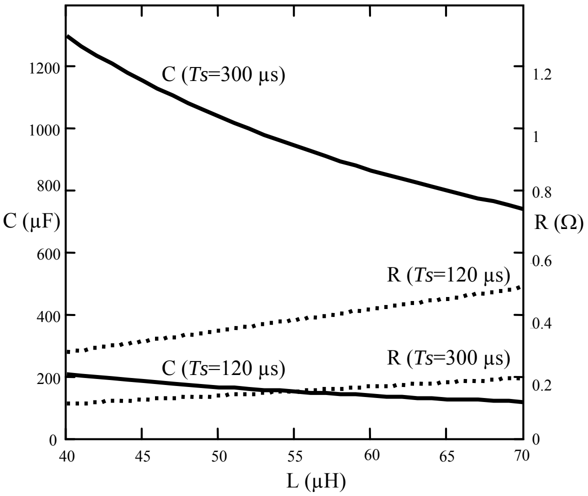

Figure 5. Values of L, C, and R needed for best linearity for the minimum and maximum slope lengths.

Fig. 5 shows a choice of values for the maximum and minimum slope lengths of 120 µs and 300 µs. By varying the value of C for a particular fixed value of L one can adjust the zero crossing time of the decreasing load current. To maintain the required linearity R must also be adjusted to an appropriate corresponding value. Physical constraints in the circuit (conductor sizes, transmission cable lengths, etc.) limit the minimum value of series resistance possible. This in turn imposes a limit on the maximum value of C and hence the minimum value of L. The choice of total inductance in the primary branch of the circuit is also determined by a number of other practical considerations such as the voltage level of the primary power supply, the value of the primary capacitor and the preferred rise-time.

The principal disadvantage of this method to vary the slope length over a reasonably large range is the difference in capacitor value needed to produce the minimum and maximum slope lengths. In this application, for a total L of 50 µH, the value of C would need to be varied between 180 µF and 1000 µF to produce the 120 µs and 300 µs slope lengths respectively. Previous proof-of-principle tests of the multi-turn injection scheme [1, 2] employed bumper power supplies using this principle of slope variation, albeit over a different range of slope lengths. Change of slope length required manual intervention to connect different capacitor values; an alternative would have been a programmable high-current switching array. The granularity of the slope length adjustment was dependent on the number of different capacitor values available for selection.

2) Variation of initial charge on the capacitor C

An alternative method to adjust the slope length is to pre-bias the freewheel capacitor with a negative voltage. The mechanism can be understood by looking at the basic circuit equations. If the forward voltage drop across diode D is ignored then the slope current, I_{slope}, can be described by Eq. 1

$$I_{slope} = \frac{I_{pk}}{\sin\phi} \cdot e^{-\alpha \cdot t} \cdot \sin(\beta \cdot t + \phi) \qquad (1)$$

where $\alpha = \frac{R}{2 \cdot L}$; $\omega = \frac{1}{\sqrt{L \cdot C}}$; $\beta = \left|\sqrt{\omega^2 - \alpha^2}\right|$ and I_{pk} is the current in the inductor at the instance of opening switch S.

$$\phi = \arcsin\left(\frac{-\beta}{\sqrt{\left(\alpha - \frac{Vb}{L \cdot I_{pk}}\right)^2 + \beta^2}}\right) \qquad (2)$$

The phase angle ϕ is given by the expression shown in Eq. 2; applying a bias voltage on the freewheel capacitor, C, changes the initial conditions and introduces the term $-\frac{Vb}{L \cdot I_{pk}}$ in the denominator.

The slope length T_s is given by setting $I_{slope} = 0$, $t = T_s$ in Eq. (1) and re-arranging to give Eq. (3).

$$T_s = \frac{-\phi}{\beta} \qquad (3)$$

As the magnitude of the negative bias voltage increases ϕ, and consequently T_s, tend towards zero.

It can be seen from Eq.2 that ϕ depends not only on Vb but also on the peak load current. The peak load current is directly proportional to the primary voltage Vp thus if Vb is programmed to be proportional to Vp, unwanted change of slope length with varying load current amplitude can be eliminated. Fig. 6 shows the variation of the slope length, T_s, plotted against the negative bias voltage on the freewheel capacitor, C, for a peak load current of 1.2 kA, with fixed L=50 µH and fixed R=0.1 Ω, for four different values of C. It can be seen that to ensure the slope range is covered a value of at least 1000 µF is required.

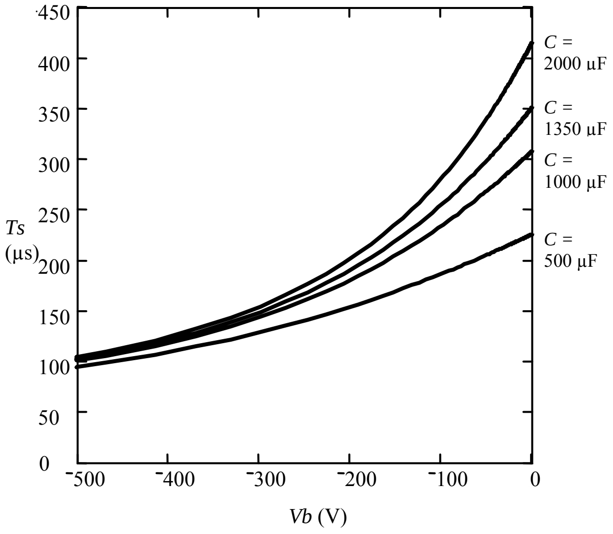

Figure 6. Variation of slope length, T_s, with bias voltage for I_{pk}=1.2 kA.

Mathcad™ simulations show that through careful optimization of the value of R, for the nominal slope of 210 µs, linearity of less than ± 0.5% can be achieved. If R is fixed then changing the slope length from the nominal value will result in a degradation of the slope linearity; the maximum excursion from an ideal slope being - 1 % for Ts=120 µs and + 3 % for Ts=300 µs. These linearity excursions can be realigned to fall within the required constraints by the judicious use of slightly shorter and slightly longer values of Ts, respectively.

D. Detailed implementation of the circuit.

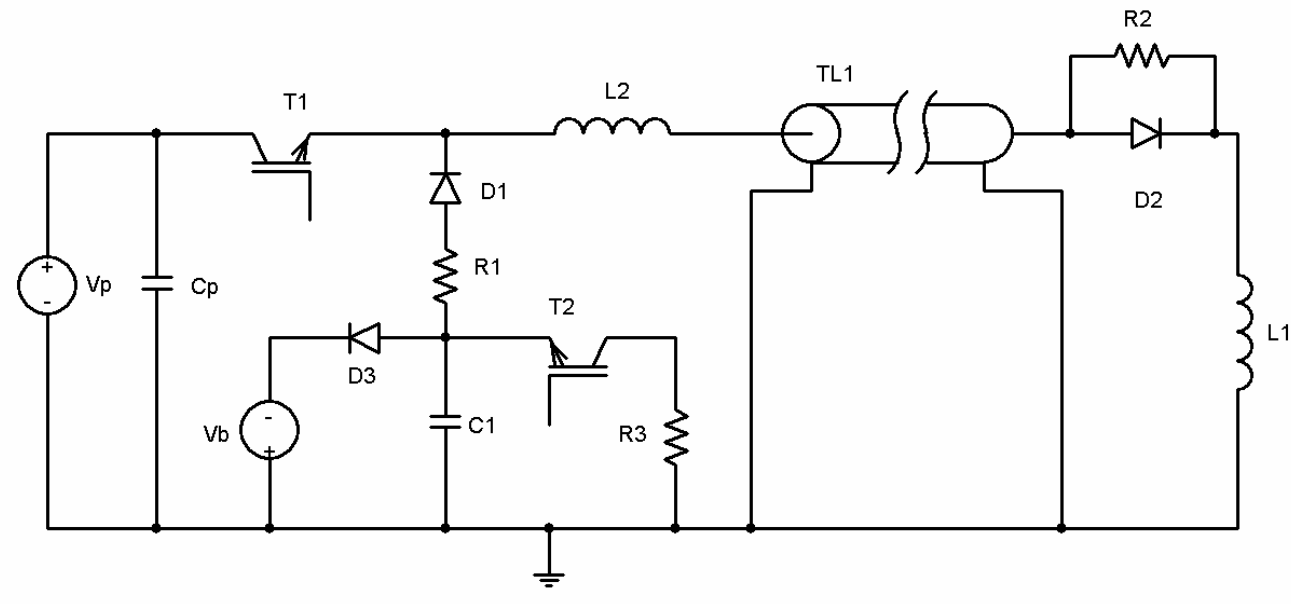

Figure 7. Detailed implementation of the circuit using a negative bias to adjust slope length.

A detailed implementation of the proposed circuit using the negative bias method is shown in Fig. 7. Extensive prototype testing of this circuit has validated the negative bias voltage method of slope adjustment for the required peak current over the full range of requested slope lengths.

T1 is an IGBT that serves as the switch S shown in Fig. 2. L2 is the required additional series inductance, of approximately 30 µH, and TL1 is a 25 m long transmission line connecting the power supply to the magnet, L1. Diode D2 is necessary to suppress oscillations induced in the load current, due to the transmission line, at the turn-off of T1. Resistor R2 is required to discharge the capacitance of the transmission line after each pulse.

T2 and R3 comprise a discharge circuit for C1 that is activated after each pulse cycle; C1 is charged to a higher negative voltage during each pulse and its voltage level must be re-adjusted to the correct bias level before the next cycle. D3 protects the bias power supply, Vb, from the increased voltage on C1 during the pulse.

As the relationship between T_s and Vb is not linear, a look-up table or similar translation of the function would facilitate programmable adjustment of the slope length.

III. SUMMARY

The LEIR Injection Bumper System will use a pulsed power supply incorporating a freewheel circuit to produce the required quasi-linear decreasing current slope. The slope length will be adjustable, over a pre-determined range, by using a variable bias voltage on the freewheel capacitor. The complexity introduced by the use of a bias power supply is more than compensated by the availability of continuous variation of the slope length, as opposed to step-wise variation implicit in the alternative method described. In addition, the need for a large number of different capacitors of various values, requiring either manual intervention or the provision of a high current switching array to connect or disconnect them from the circuit, is obviated.

IV. REFERENCES

[1] A. Fowler and K.-D. Metzmacher, "The Injection Bumper System for LEIR Ion Tests”, PS/CA/Note 98-22 (Tech.), CERN, (1998).

[2] J. Bosser et al., “Recent Lead Ion Storage Tests on LEAR”, CERN/PS 97-37 (HP), 1997 Particle Accelerator Conference, 12-16.5.97, Vancouver, B.C., Canada.