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Generation of Multiple Bipolar Voltage Pulses for a Phase Rotation LIA[1]

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Abstract

In the year 2000, a design concept of a Neutrino Factory based on Muon Storage Ring was studied at FNAL. To treat high energy spread of muons that come out of a target and decay channel and are to be accelerated before they go into the storage ring, a phase rotating scheme using a long-pulse accelerating system has been proposed. In this system accelerating voltage is to be shaped to correct the energy spread. To implement this approach, the pulse power system has been suggested that allows forming a bipolar accelerating voltage pulse with the predefined shape. This report addresses some issues of the pulse shape optimization and describes main features of the accelerating system comprising an accelerating structure similar to that of a linear induction accelerator (LIA) and a pulser that drives it.

I. Introduction

The concept of the FNAL Neutrino Factory (NF) and its draft parameters have been introduced in [1]. The muon beam is produced by decay of pions in a drift channel. The energy spread of this beam is too high to allow its direct injection into the NF accelerating structure. One of the ways to reduce this spread is to use a differential acceleration by applying a time-depending accelerating voltage after an energy-time correlation is developed in the drift channel. This procedure was named "phase rotation" in accordance with the transformation of the longitudinal phase space occupied by the beam. One of the ways of performing the phase rotation procedure is using an accelerating system similar to that of a linear induction accelerator (LIA). A possibility of using LIA for this purpose has been investigated in [2]. Although it has been shown that this approach is theoretically quite feasible, there are several features that make its implementation technically challenging:

- Muon energy spread to be compensated is about 200 MeV;
- Because of the limited life time of muons, the length of the LIA channel must be of the order of 100 meters that forces using bipolar voltage pulses supporting State-of-Art accelerating gradients.
- Transverse size of the beam defined by its emittance is rather high. Needed efficiency of the beam transportation can only be reached if high strength axial magnetic field created by superconducting solenoids is used everywhere in the channel.
- Repetitive pulse regime with 15 Hz basic frequency is to be used to get needed neutrino generation rate. The burst of four 150-ns pulses separated by three 600-ns gaps forms one macro-pulse that is to be repeated.
- Maximal muon beam current is too low to provide a significant load to the LIA induction cell. The major part of the LIA power consumption is defined by power loss in the ferromagnetic cores of the LIA induction cells.

To approach the system development, a simple model of the accelerating section has been generated that allowed further steps.

II. Accelerating Section Layout

One of possible layouts of the LIA accelerating section is shown in Fig. 1.

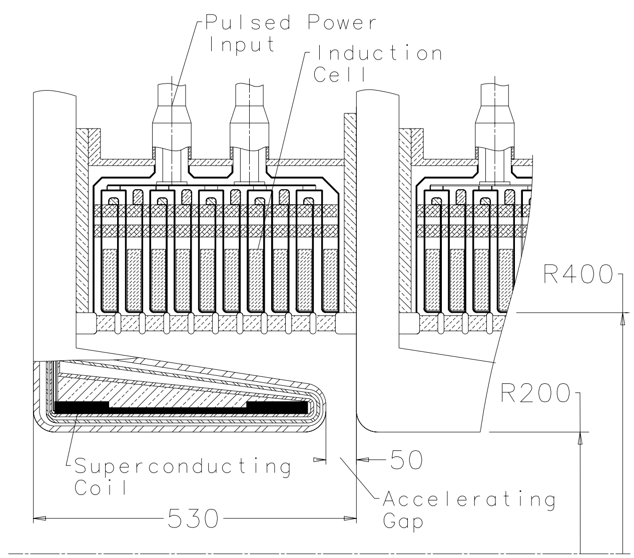

Figure 1. Ten-cell accelerating section

Ten induction cells are fed in parallel by a high power pulser. The sum of the induction voltages of the cells is applied to the accelerating gap with the use of a tapered adder. Inside the adder, a superconducting solenoid is placed that provides magnetic field of 3 T in

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the 40-cm bore. Identical sections are stacked in series to provide needed energy gain. Because of the accelerating gap, magnetic flux of the solenoids penetrates into the space outside the bore where ferromagnetic induction cores are located. One of the LIA section design goals is to insure that this magnetic field does not deteriorate performance of the inductors. It is possible to reduce the fringe field if to make accelerating gap smaller and increase the radial distance from the solenoid to the induction cores. For the geometry of the section shown in the Fig. 1, maximal magnetic field of this nature in the cores is about 200 Gs when the axial field in the section bore reaches 3 T. According to [3], magnetic field of 270 Gs directed along the axis of a toroidal core wound using 2HCP nano-crystalline alloy tape does not significantly change pulse magnetization properties of the core. So, we can expect nominal core performance with maximal field level of 3 T. Although using lower magnetic field requires larger bore, it does not result in a significantly higher core radius because fringe field is proportional to the bore magnetic field. On the other hand, lower field level helps to reduce the energy stored in the channel and make protection system simpler.

Superconducting solenoid can be wound using cable made of Nb-Ti wire. To reduce fringe fields, it has additional windings near the edges. Design of the solenoid is quite straightforward; several approaches are described in [4] and [5].

III. Accelerating Voltage Pulse Shape Optimization

The accelerating field in the Phase Rotating System must be shaped in time so that particle energy distribution could be corrected. The required pulse shape has been found in [2] and is shown on the chart in Fig. 2.

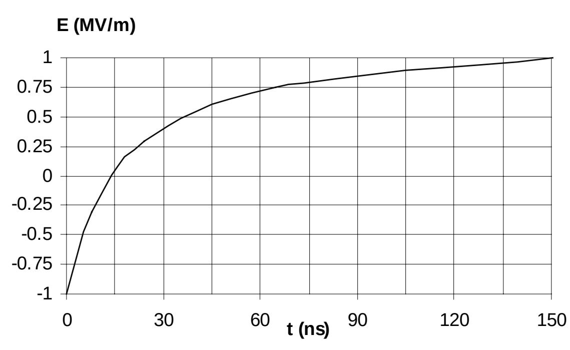

Figure 2. Typical voltage pulse shape

One part of the beam emerging out of the drift channel must receive more or less energy gain than another. Only relative accelerating gradient is important for the energy spread correction purpose, so the curve in the Fig. 2 can be moved along the voltage scale without compromising the expected result.

Multiple pulse regime of LIA work requires resetting of the induction core magnetization after the end of each pulse. Taking into the account the 600-ns gaps between the pulses, it would be good to design a pulse that resets the core automatically. In this situation, the pulse must be bipolar, and volt-seconds of the negative and the positive parts of the pulse, including the pulse rise time and fall time, must be equal. To reduce core volume, pulse rise must be as short as it is reasonably possible. This results in the requirement of a powerful, low-impedance pulser. Although final optimization can be made after a proper pulser scheme is found, it is possible to approach the problem using simple approximation of the voltage pulse:

$$E(t)=\begin{cases}\dfrac{E0}{1-e^{-\frac{t1}{\tau1}}}\cdot(1-e^{-\frac{t}{\tau1}})\ldots\ldots\ldots\ldots\ldots\ldots\ldots 0<t\le t1\\ E0+E1\cdot(1-e^{-\frac{t-t1}{\tau0}})+\dfrac{E2}{T_p}\cdot(t-t1)\ldots t1<t\le t1+T_p\\ E(t1+T_p)\cdot e^{-\frac{t-(t1+T_p)}{\tau2}}\ldots\ldots\ldots\ldots\ldots\ldots t1+T_p<t\end{cases}\qquad \text{Eq. 1}$$

In this expression, $t1$ is the pulse rise time, T_p is the duration of the active part of the pulse, $E0$ is the level of the accelerating gradient in the very beginning of the pulse, and $E1$, $E2$, $\tau0$, $\tau1$, and $\tau2$ are the parameters that define details of the pulse shape. With $E1$ = 1.55 MV/m, $E2$ = 0.45 MV/m, and $\tau0$ = 15 ns, this expression fits nicely to the requested active part of the pulse (Fig. 1) with maximum deviation of not more than 7.5%. The front and the end parts of the pulse can be adjusted independently of the central part by changing $\tau1$ and $\tau2$ to allow zeroing the pulse volt-seconds for different levels of E0. For the ideal pulse expressed by (1) with $\tau1 = \tau2 = 0$, the initial value of the gradient that results in zero volt-seconds is $E0 \approx$ -1.65 MV/m. In this case, minimal volume of the core magnetic material is required that is defined by the volt-second integral over the negative part of the pulse. If the front rise time increases, absolute value of the initial gradient E0 will drop, and increased volt-seconds will result in larger core volume.

Having analytical expression for the accelerating pulse shape allows us to estimate core power loss. The model that describes energy loss for a core made of a metal ribbon was developed by R. Smith [6]. In our analysis we will take into account that the induction core magnetization rate is very high, so the saturation wave domain movement mechanism is responsible for the major part of power loss. For example, for the nano-crystalline alloy FT-1H, at the magnetization rate of more than 10 T/μs, eddy currents described in terms of a saturation wave domain movement explain about 95% of the total core power loss. Following [6], we can write down for the magnetic field $H(t)$ driving the saturation wave domain movement:

$$H(t)=\left(\frac{d^2}{4\rho}\right)\cdot\left(\frac{\Delta B(t)}{2B_S}\right)\cdot\left(\frac{dB}{dt}\right)\qquad \text{Eq. 2}$$

where $\Delta B(t) = B(t) + B_r$ is an efficient flux density swing, B_S is material saturation field, B_r is residual field, d is ribbon thickness, and ρ is specific resistance of the core material.

Power loss per a unit of a magnetic material volume is described by the expression:

$$p(t) = H(t) \cdot \frac{dB(t)}{dt} \qquad \text{Eq. 3}$$

that gives after using Eq. 2:

$$p(t) = \left(\frac{d^2}{4\rho}\right) \cdot \left(\frac{B(t) + B_r}{2B_S}\right) \cdot \left(\frac{dB}{dt}\right)^2 \qquad \text{Eq. 4}$$

We can find $\frac{dB(t)}{dt}$ and *B(t)* if we know voltage pulse shape, for example as defined by the expression (1):

$$\frac{dB}{dt} = \frac{E(t)}{S} \qquad \text{Eq. 5}$$

where *S* is the effective core cross-section per one meter of the channel length.

Table 1 compares required core cross-sections $S_{\min}$ of a 1-m section, maximal power loss per one meter of the LIA length $p1_{\max}$, and average power loss P_{av} of a 100-m LIA (four-pulse regime and 15 Hz operation frequency) for three accelerating pulses that differ by the initial accelerating rate. The power loss was calculated using Eq. 4 with the assumption that cores were fabricated from METGLAS 2605SC amorphous alloy ribbon with thickness of 25 μm. Specific resistance of this alloy is $1.3*10^{-6}$ Ohm·m.

Table 1. Pulsed power system optimization

***E*0 (MV/m)**	**$S_{\min}$ (m²)**	**$p1_{\max}$ (GW/m)**	**P_{av} (MW)**
-1.00	0.045	5.54	2.75
-1.25	0.030	11.65	2.64
-1.5	0.016	18.9	2.14

It is possible to see from this table that the core cross-section and average power are minimal for the case with *E0* = -1.5 MV/m although pulsed power is maximal in this case.

Whatever pulse shape is chosen, in accordance with Eq. 4, it is possible to reduce power loss by using cores with larger cross-sections thus lowering the core flux density. Higher price to pay for the cores can be compensated by lower power bills. Table 2 shows maximum power consumption $\boldsymbol{p1_{max}}$, energy loss ***w1*** per one pulse per one meter of the channel length, and average 100-m LIA power $\boldsymbol{P_{av}}$ depending on core cross-section $\boldsymbol{S_{core}}$. per one meter of the LIA length. Initial acceleration rate of -1.5 MV/m was used here because it corresponded to minimal power loss according to Table 1.

Table 2. Core cross-section optimization

S_{core} (m²)	0.016	0.02	0.03	0.04	0.05
$p1_{\max}$ (GW/m)	18.9	11.25	5.47	3.1	1.97
***w1* (J/m)**	360	230	103	58	37.2
P_{av} (MW)	2.14	1.4	0.62	0.35	0.223

Even this simple attempt to optimize the parameters of the LIA shows that there must be an optimal cross-section that corresponds to minimal effective cost that in the simplest case depends only on costs energy and on the induction cell core cost.

Another factor that can limit our choice of the system features is availability of a pulsed power source with needed output parameters. At this stage it is important to come out with an appropriate scheme of a pulse circuit to feed the LIA section.

IV. Pulsed Power System

A conceptual scheme of the pulse generator is shown in Fig. 3.

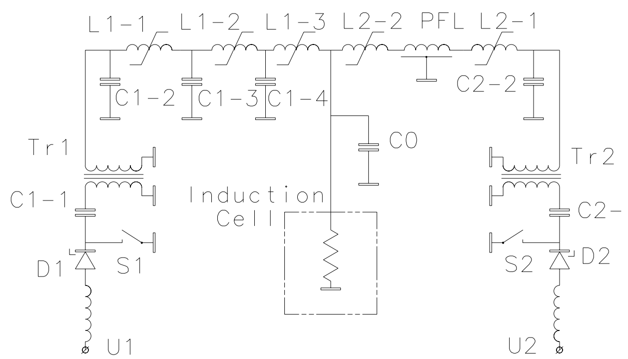

Figure 3: Conceptual scheme of the pulse generator.

The generator has been designed to feed a ten-cell induction section similar to shown on the picture in Fig. 1. All the ten cells in the section are connected in parallel. Each induction cell uses a tape-wound ferromagnetic core made of nano-crystalline alloy. The cross-section of each cell core is about 20 cm². Because the average core diameter is about 90 cm (see Fig. 1), the volume of magnetic material per one core is about 5700 cm³. Although, the impedance of the induction cell is quite nonlinear due to nonlinear nature of power loss, for this study linear resistance was used to represent the load of the generator.

There are two parts in the generator: the “charging” part, located on the left side of the picture in Fig. 3, and the “forming” part on the right side of the picture. The “charging” part sets voltage of the capacitor C0 to the initial level of -75 kV. The “forming” part of the generator forms the output voltage that increases from the level of –75 kV up to +25 kV. The working part of the voltage pulse applied to the induction cell is formed by the discharge of the pulse forming line (PFL) and the capacitor C0. To ensure the necessary charge rate of the capacitor C0, a three-stage magnetic compression circuit is used. The energy is delivered to this compression circuit by the storage capacitor C1-1 via the pulse transformer Tr1. The PFL in the “forming” part of the generator is charged via the single-stage magnetic compression circuit L2-1÷C2-2. The energy for this part of the circuit is stored in C2-1, and Tr2 is used to get the needed PFL voltage.

Fig. 4 shows the output voltage pulse

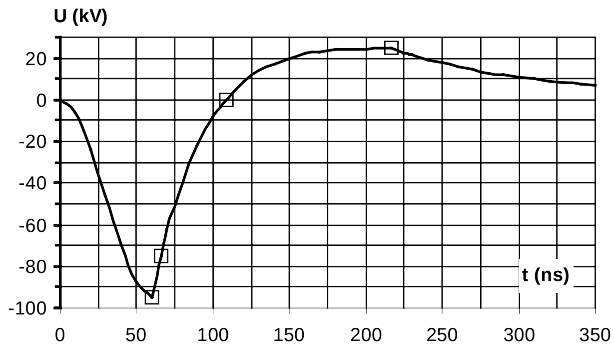

Figure 4. Output voltage pulse applied to the inductors in the LIA section.

During the time interval from 0 till 60 ns, the “charging” part of the generator charges the capacitor C0 to -95 kV. Starting at 60 ns, a natural discharge of the capacitor C0 occurs through the induction cell. Simultaneously the magnetic switch L1-3 magnetizes increasing its resistance to the positive voltage coming from PFL through the reactor L2-2. Staring at 67 ns, the reactor L2-2 opens and the PFL starts to recharge the capacitor C0. Meanwhile, the capacitor C0 continues discharging through the induction cell. During the time interval from 67 ns till 111 ns, the magnetic core of the switch L1-3 restores its high impedance that prevents the energy transfer from the PFL to the capacitor C1-4 during the positive part of the voltage pulse. To make it work, the negative volt-second area (from 60 ns till 111 ns) must be, at least, equal to the area under the positive voltage pulse part (from 111 ns till 217 ns).

The time duration of the negative and positive parts of the voltage pulse (not only of the active part of the pulse) has been chosen to make their volt-second areas equal to each other. As a result, the magnetic recovery of the induction cell core is reached automatically: when a voltage pulse is over, the system is ready to accept the next one. The next pulse can start immediately after the previous one. The description of the pulser for generation of the burst of four sequential pulses as it was required by the Neutrino Factory specifications is presented in [7].

As particles are moving along the LIA, their energy distribution and pulse length are changing. To make the accelerating voltage pulse shape adjustments, certain variations of the capacitance C0, the inductance L2-2, and the charging voltage of the PFL can be made.

The initial “charging” voltage level (-95 kV in our case) depends on the duration of the natural discharge of the capacitor C0. This duration and the output voltage level become lower when asymmetric voltage pulse with voltage shifted to the negative part of the voltage scale is used to feed the induction cell.

To get needed differential acceleration rate, 20 induction cells per each meter of LIA length are used, so the first part of the beam feels the accelerating gradient of -1.5 MV/m and the last part of the beam sees +0.5 MV/m.

Impedance of the described circuit cannot be made arbitrarily small. Nevertheless, it appears feasible to use one generator to feed 10 inductors (0.5-m length) in parallel. This sets a natural scale of 0.5 m to the LIA accelerating section length and its possible increment. The final choice of this length is to be done based on other requirements of mechanical, magnetic, or other nature.

V. Summary

The approach to the pulsed power system of the LIA-based Phase Rotation Channel of a Neutrino Factory has been developed that allows generation of multiple pulses. It has been shown that using asymmetric bipolar voltage pulse for beam acceleration results in the reduced power loss and core volume in the induction accelerating system. Some modest R&D efforts are required to adjust the developed scheme of the generator to the nonlinear impedance of the induction cells.

VI. Acknowledgement

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VII. References

1. R.B.Palmer, ”Neutrino Factory Draft Parameters”, Muon Collider Collaboration Note #46, Sept.. 1999; Available: http:\\www-mucool.fnal.gov/mcnotes.
2. V.Balbekov, N.Holtkamp “Phase Rotation of Muons by Induction Linac”, Muon Collider Collaboration Note #59, Oct. 1999; Available: http:\\www-mucool.fnal.gov/mcnotes.
3. G.Mamaev, et al. "LIA Core Magnetization in Fringe Magnetic Field", MRTI RAS Rep, Russia, Jan. 2000, Available: http://windoms.sitek.net/~mrti204/
4. L.Tkachenko, et al. "Muon Transport Channels with Longitudinal Magnetic Field", presented at PAC-2001, Chicago, June 18 - 22, 2001.
5. L.Reginato, et al. "Muon Phase Rotation Using an Induction Linac", presented at PAC-2001, Chicago, June 18 - 22, 2001.
6. Carl H. Smith "Application of amorphous magnetic materials at very-high magnetization rates" J. Appl. Phys. 67 (9), 1 May 1990, pp. 5556 - 5561.
7. V. Kazacha, et al. "Pulsed Power System of Linear Induction Accelerator for FNAL Neutrino Factory", presented at PAC-2001, Chicago, June 18 - 22, 2001.