DEVELOPMENT OF A FAST TRAVELING-WAVE BEAM CHOPPER FOR THE SNS PROJECT*

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Abstract

High current and stringent restrictions on beam losses, below 1 nA/m, in the designed linac for the Spallation Neutron Source (SNS) require clean and fast – with the rise time from 2% to 98% less than 2.5 ns – beam chopping in its front end, at the beam energy 2.5 MeV. The development of new traveling-wave deflecting current structures based on meander lines is discussed. Three-dimensional time-domain computer simulations with MAFIA are used to study transient effects in the chopper and to optimize current structure design. Two options for the fast pulsed voltage generator – based on FETs and vacuum tubes – are considered, and their advantages and shortcomings for the SNS chopper are discussed.

1 MEBT CHOPPER SYSTEM

The SNS is a next-generation pulsed spallation neutron source designed to deliver 1 MW of beam power on the target at 60 Hz in its initial stage [1,2]. It will consist of a 1-GeV linear H^- accelerator and an accumulator ring. The SNS storage ring accumulates the linac beam during a few hundred turns (a macropulse, about 1 ms) using H^--injection through a carbon foil. The beam injected into the ring is stacked into a single long bunch, and the linac macropulse must be chopped at near the ring revolution frequency 1.188 MHz to provide a gap required for the kicker rise time during a single-turn ring extraction. The final clean beam chopping in the linac is to be done in the Medium Energy Beam Transport (MEBT) line.

The MEBT transports 28 mA of peak beam current from a 2.5-MeV 402.5-MHz RFQ to a drift-tube linac. A 0.5-m space is allocated for the chopper that deflects the beam into a beam stop during the 35% beam-off time. The chopper parameters are summarized in Table 1.

Table 1: MEBT Chopper Specifications

Parameter	Value	Comment
Beam energy	2.5 MeV	β=0.073
Length	≤0.5 m	Shorter is better
Gap	1 cm	adjustable
Pulser voltage	±900 V	Currently achievable with FETs
Deflection angle	18 mrad	
Chopping period	841 ns	
Duty factor	35 %	65 % beam on
Rise / fall time	< 2.5 ns	2–98 % (final goal)

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To mitigate the effects of a partial chopping or small errors in the timing system, an identical “anti-chopper” is placed in the MEBT line at an optically symmetric point from the chopper to return uncollimated beam to the axis. Two preliminary chopping stages (at the ion source and in the LEBT line, at 100 keV, see [2]) are introduced to reduce the beam power deposited at the MEBT beam stop.

At any given moment of beam passing through, there are about ten bunches along the chopper length. Even having an ideal pulse generator, the only way to avoid partially chopped bunches is to apply a traveling-wave current structure. The deflecting electric-field pulse fills the chopper with the phase velocity along the beam path matching the beam velocity and propagates together with the beam. The bunches following the pulse front are fully deflected while those ahead of the front are not disturbed. Providing the field-pulse front (and its end) shorter than the bunch-to-bunch spacing (2.5 ns, or about 5 cm) is the most challenging requirement to the chopper system. As an initial goal, the rise/fall time below 5 ns is acceptable; it will lead to one partially chopped bunch at the front and the end of each chopper pulse.

2 CHOPPER CURRENT STRUCTURE

A traveling-wave chopper for $H^\pm$ beams at 750 keV [3] has been working successfully for many years at LAMPF. It provides the rise time of about 7 ns, mostly due to the pulse modulator. Its coax-plate current structure itself is capable of providing a pulse front about 2-3 ns with an overshoot on the 10% level ringing for a few ns. The 1-m long structure consists of two parallel plates, each interfaced with many small strip segments connected with coaxial cables on the reverse side of each plate to form a continuous circuit along the structure. The voltages on the upper and lower plates are synchronized and have opposite signs so that the resulting vertical electric field deflects the beam. The structure rise and fall time limitations are caused by stray capacitance between the segments and by multiple coax-to-segment transitions.

A new current structure based on a meander line with separators (Fig.1) has been proposed in [4]. A strip line forming the meander can be either straight or notched (as the one shown in Fig. 1). The line parameters are adjusted to provide the line characteristic impedance 50 Ω. The meander bends are chamfered to avoid pulse reflections.

The separators (or guard barriers) rising from and electrically connected to the ground plane are used to reduce the coupling between the adjacent sections of the meander line, see in Fig.2. The new design has no multiple coax-to-plate transitions and is easier for manufacturing.

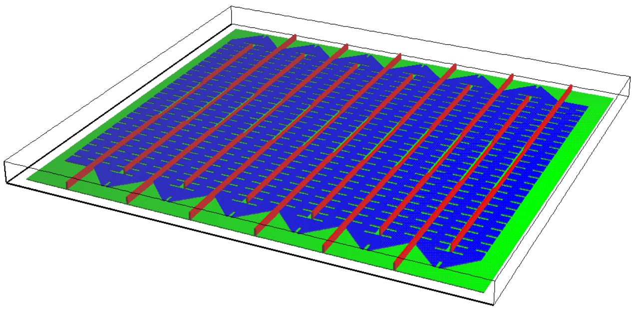

Figure 1: 1/4-length model of meander current structure: notched meander strip line (blue) above the ground plate (green) with separators (red), cf. Fig.2. Only the lower plate is shown.

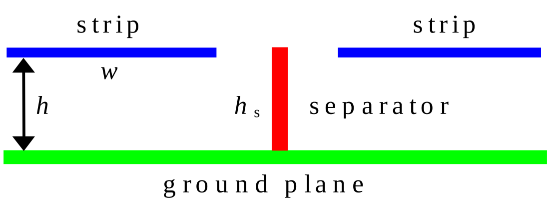

Figure 2: A partial vertical cut in the beam path plane of the meander current structure: the separator is inserted between two adjacent pieces of the transmission line.

3-D time-domain simulations with the electromagnetic simulator MAFIA [5] have been used to study transient effects in the current structure. It was shown [4] that even without separators, the meander structure has a rise time 2–2.5 ns; with separators it can be reduced down to 1–1.25 ns, depending on the separator height. The structure fall time was found to be about the same as the rise time. High separators, however, reduce the effective field on the beam path by 10–20% depending on their height h_s.

Our previous work [4] dealt mostly with straight-strip meander structures. Using a notched strip line in the meander instead of a straight one has some advantages. First, the notches provide an additional inductive load that slows down the wave along the strip. It increases the field efficiency due to a larger ratio of the strip width w to the strip-to-strip gap width g: the notched-strip width w is 8 mm compared to 5 mm for a straight line. The meander width transverse to the beam is about 11 cm, h=1 mm and g=2 mm in both cases. In addition, the notches also reduce the magnetic coupling between adjacent strips since the wave magnetic field is concentrated closer to the strip center. As a result, our recent efforts have been directed toward optimizing the notched-strip design.

For earlier simulations [4] we needed to load a TEM wave into the structure. The latest version of MAFIA [5] allows simply to feed the strip with a voltage having any time profile. We have used voltages shaped as either step-functions (often smoothed by a squared *sin* to filter out very high frequencies) or as finite-length pulses. As the voltage pulse propagates along the structure, the electric field on the beam path is recorded. As an example, Fig.3 shows the deflecting field created by a voltage pulse with 1-ns sin^2 front, flat top at 1 kV for 3 ns, and 1-ns sin^2 end, in the full-length 50-cm model of the type shown in Fig.1. Such a pulse would kick out exactly two linac bunches. As the pulse propagates, its shape is slightly distorted by developing an overshoot, but its front and end remain well within 2-ns range, see also Fig.4.

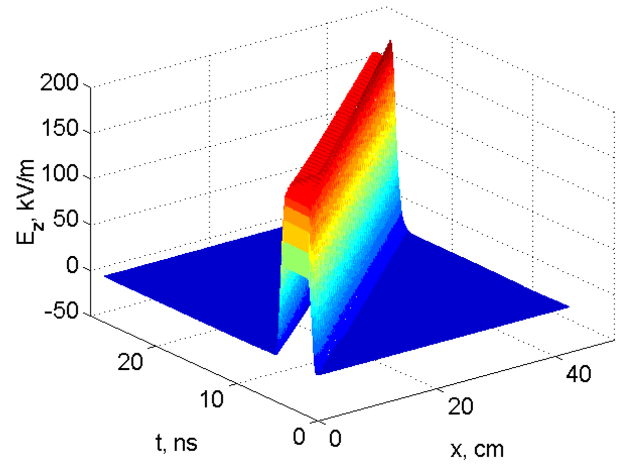

Figure 3: Deflecting field on the beam path versus time and position in the notched-strip meander structure for a 1-3-1-ns 1-kV driving pulse.

Cross-sections of the surface plot in Fig.3 for a given position x along the structure show time dependence of the field at this location, cf. Fig.4. Straight-strip meanders produce slightly larger pulse distortions, see in [6].

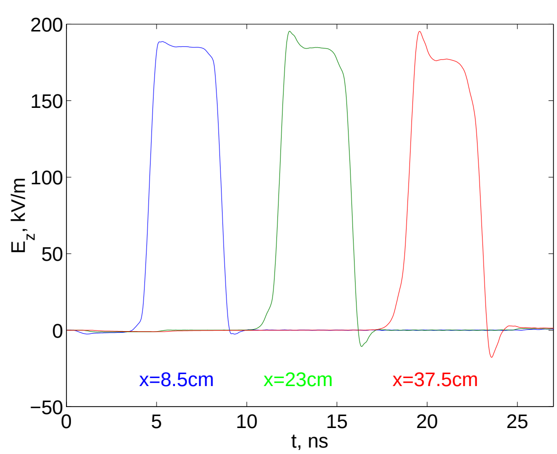

Figure 4: Deflecting field versus time in 3 different points on the beam path in the notched-strip meander structure.

Cross-sections of Fig.3 taken at given time t produce snapshots of the deflecting field as shown in Fig.5. Small wiggles on the pulse tops are due to differences of the field in points above the middle of the strip and above the separators. In fact, these field variations will even help to spread the deflected beam slightly on the beam stop.

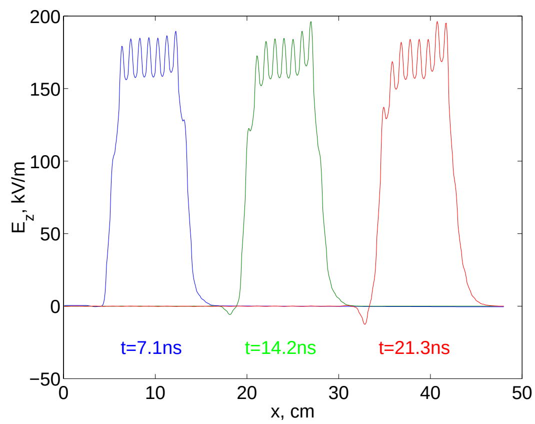

Figure 5: Snapshots of the deflecting field on the beam path in the notched-strip meander structure (cf. Fig.3).

As a result of our design optimization, the notched-meander structure looks as shown in Fig.1. Extra notches on the bends have been added to eliminate reflections. To increase the effective field on the beam path without increasing the rise time, the profiled separators have been introduced: they are low (flash with the strip line) near the beam and higher near the edges, see Figs.1-2.

3 CHOPPER PULSE GENERATOR

There are two technologies applicable to generating the required chopping voltage. These are the planar triode vacuum tubes and power FET devices.

Planar triodes, such as the Eimac 8940, could be used as switches to generate the required pulses. A number of difficulties would be challenging to overcome. The duty factor rating of these small triodes is a factor of ten lower than needed, so multiple tubes must be connected in parallel. Increasing the number of tubes increases the stray capacitance and the current rise time. These tubes are designed for operation at several kilovolts, which results in high grid currents at low voltage operation (such as 2 kV). Excessive grid power dissipation is a concern [7]. Generating the grid-drive will be as difficult as producing the output pulse. On the positive side, sub-nanosecond rise time has been demonstrated with these tubes at low duty factors [7,8] and a previous LANSCE chopper using six tubes produced 3-ns rise times and 4.5-ns fall times at 500 volts with similar duty factors [9].

Power FETs, such as the DEI 102N02, are capable of switching high currents at the <1-kV level at high repetition rates. A FET-switched pulser should be able to meet all of the specifications fairly easily, except for the rise time. The available FETs from current manufacturers are inherently limited to rise times on the order of 3-4 ns, with 5 ns being a demonstrated number [10]. We feel that the power FET devices are the best choice for the switching technology for the chopper application.

Starting next year we will build and test a proof-of-principle chopper pulser using FET devices that are currently available. This will be a low-average-power system whose purpose is to verify what level of performance can be expected using existing technology. We will build both a positive-output and negative-output polarity pulsers that are capable of generating 900-V pulses across 50-Ω loads. Each pulser consists of two high-voltage FETs, their gate-drive circuits, optical trigger links, an impedance-matched chassis assembly, power supplies and instrumentation. Output rise times and fall times are expected to be on the order of 5 ns.

In parallel with the proof-of-principle chopper pulser work we will attempt to develop FET devices which are faster than presently available. This entails fabricating new FETs whose bulk-silicon and doping characteristics will be specifically optimized for fast switching. Directed Energy Inc. (DEI) feels [10] that they can produce a significantly faster device, but the development cost will be significant. We will contract out this work to a suitable company with experience in the production of similar devices. If this effort is successful, we will incorporate these new FETs into our proof-of-principle pulser design.

4 CONCLUSIONS

A new current structure based on a meander line has been developed. The 3-D time-domain modeling shows that the structure is capable to provide the rise and fall times on the order of 1 ns. Further simulations will include more engineering details like supports, as well as beam dynamics and PIC-simulations. Manufacturing of the prototypes and their measurements are also planned.

The voltage generator development remains the most important and challenging issue. We will proceed with the proof-of-principle pulser design using currently available technology, while continuing to work with manufacturers on development of faster powerful FETs.

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