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TRAVELING-WAVE CHOPPER STRUCTURES FOR LANSCE MODIFICATION PROJECT

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Abstract

The Los Alamos Neutron Science Center (LANSCE) accelerator complex delivers both protons and negative hydrogen ions with various beam time patterns simultaneously to multiple users. The LANSCE linac front end is still based on Cockcroft-Walton voltage generators. An upgrade of the front end to a modern, RFQ-based version – a part of the LANSCE Modernization Project (LAMP) – is now in the conceptual design stage. The LAMP will need fast beam choppers both in the low-energy transport (LEBT, 100 keV) before RFQ, and in the medium-energy transport (MEBT, 3 MeV) after RFQ. We use CST modeling to develop fast traveling-wave current structures for LAMP MEBT and LEBT beam choppers. A few structure types: plate-coax helix, meander-folded stripline on high-dielectric-constant substrate, and double-helix – are considered and compared. The structures must provide short rise / fall times of the deflecting electric field (1-ns class in MEBT), while still making possible for the chopper pulse generators to deliver the required voltages at high repetition rates.

INTRODUCTION

The Low Energy Beam Transport (LEBT) chopper creates required beam time structures by chopping out (removing by deflecting from the beam path) unwanted parts of a continuous beam transported in LEBT from the ion source to the RFQ. The unchopped parts of the beam propagate through the LEBT, while the deflected parts are deposited on an absorbing target. The chopper system must turn deflection on and off within a short time interval, because the beam parts within the pulse front and end will be only partially deflected and will form unwanted tails of the beam pulse downstream.

The Medium Energy Beam Transport (MEBT) chopper removes unwanted beam bunches by deflecting them to a target from a bunched beam transported through the MEBT from RFQ to the Drift-Tube Linac (DTL) entrance. The unchopped bunches propagate through the MEBT to DTL, while the deflected bunches are deposited on a target downstream of chopper. Ideally, the system should turn deflection on and off in the time interval between the bunches to prevent partially chopped / deflected bunches.

In both cases the chopper system consists of a deflecting structure, where the beam-deflecting fields are created, and a pulse generator (pulser) that feeds the structure with voltage pulses having a needed time pattern. Required fast switching on/off of chopper deflecting fields can be achieved using traveling slow-wave chopper structures – two plates with voltage pulses of equal amplitude but opposite sign – where the deflecting field pulse propagates along the structure with the same velocity as the beam.

If a beam travels at velocity βc along the z-axis, and its deflection is in the y-direction (transverse to the structure plates), the deflecting Lorentz force per unit charge is $F_y / q = E_y + \beta Z_0 H_x$, where $Z_0 = \sqrt{\mu_0 / \varepsilon_0} = 120\pi\ \Omega$. The maximal deflecting electric field is $E_{\max} = V/h$, where $\pm V$ are potentials on two plates and $2h$ is the distance between them. Normalizing the above deflection force to $E_{\max}$, we define the chopper deflection efficiency $\eta = \eta_e - \eta_m$, where $\eta_e = E_y/E_{\max}$ is the electric efficiency and $\eta_m = -\beta Z_0 H_x/E_{\max}$ is the magnetic reduction [1, 2].

The main chopper parameters - length L, aperture $a = 2h$, and required voltage from pulse generator V – are defined by beam dynamics design. The beam deflection angle α is related to these parameters as follows:

$$\alpha \cong \frac{q}{mc^2\beta^2\gamma}\frac{\eta\Delta VL}{a} \cong \frac{q}{2W}\frac{V_{eff}L}{a}, \tag{1}$$

where q and m are the charge and mass of beam particles (protons or H^-), $\gamma = (1-\beta^2)^{-1/2}$, η is the structure efficiency defined above, $\Delta V = 2V$ is the voltage between two plates, and $V_{\mathrm{eff}} = \eta V$.

The chopper system rise and fall times depend on both system elements – structure and voltage pulse generator. If these elements have the rise / fall times t_s and t_p, correspondingly, the chopper rise / fall times can be estimated as $t_c = (t_s^2 + t_p^2)^{1/2}$. One more effect influences the chopper structure rise / fall time. Even if the voltage on chopper plates is turned on instantaneously, in the regions near the plate ends the fields vary from zero to maximal value – the edge effect. If a beam travels at velocity βc through these edge regions in the structure with aperture a, it effectively experiences field change that is equivalent to rise / fall time $t_e \approx a/\beta c$ [2]. This effect can be noticeable in LEBT, where the beam size is large while the velocity is low.

MEBT CHOPPERS

There are a few fast traveling-wave chopper structures developed since 1980s, see in [1, 2] – strip-coax helix at LANSCE [3], meander-line choppers for SNS [4] and CERN [5], and more recently, dual-helix beam deflector at FNAL [6]. These structures were designed for the proton beam energies 2-3 MeV (except LANSCE – 750 keV) and demonstrated rise / fall times t_s in the range 1 – 4 ns. Complementing them with a fast pulse generator providing high voltage amplitude (> 1 kV), especially at high repetition rate (~MHz in bursts), is more challenging.

The main requirements for LAMP MEBT choppers are defined [7, 8] by the RFQ and DTL RF frequency of 201.25 MHz, which corresponds to RF period 4.97 ns, beam dynamics design [8], and by the required beam time patterns.

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For LAMP MEBT choppers at 3 MeV ($\beta = 0.08$) we consider three following structures.

Meander Stripline

This slow-wave structure is based on a simple meander-folded 50-Ω line on solid high-purity alumina substrate (dielectric constant ε = 9.9 and loss tan δ = 1e-4 at 100 MHz) on top of a grounded metal plate as shown in Fig. 1. This design is similar to that proposed in [1] and to the double meander structure [5] implemented at CERN. The beam path is on top of the vacuum box (transparent light-blue), at height h = 9 mm from meander line.

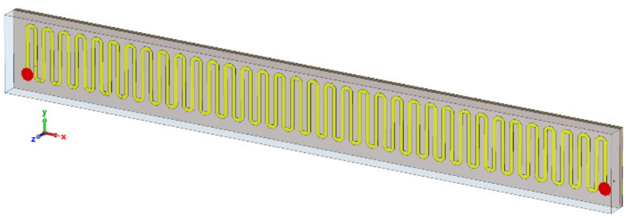

Figure 1: CST model of one chopper plate: simple meander line (copper color) on alumina substrate (gray).

The structure length along the beam path is 35 cm, the meander period is 10 mm and width b = 29.1 mm, stripline metal width w = 2.1 mm with thickness 0.1 mm. The substrate thickness is 3 mm. Time-domain modeling in CST Studio [9] gives the structure rise/fall times about 2.5 ns with deflecting efficiency η = 0.82, see [10] for details.

The rise/ fall times mainly depend on coupling between parallel segments of the meander. One can make the structure faster – reduce its rise / fall times – by reducing the coupling. This can be achieved by inserting grounded metal separators between the segments, see in Fig. 2. Here b = 25.4 mm and w = 1.64 mm.

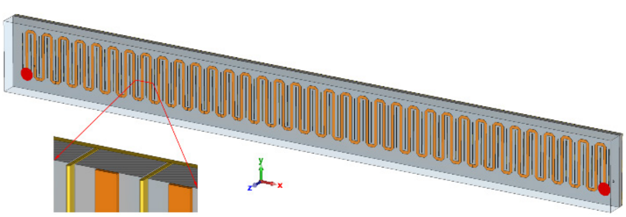

Figure 2: CST model of the meander line with grounded separators (shown in inset).

The calculated structure rise/fall times become about 1.5 ns, but the deflecting efficiency decreases to η = 0.58, see in [10]. Figure 3 shows the structure response to a short input signal with 2-ns $\sin^2$-shaped rise and fall and 5-ns flat-top for two meander structures presented above, Figs. 1-2. While the rise / fall times are acceptable, the low efficiency leads to higher required voltage amplitude, which makes the voltage pulser design more challenging.

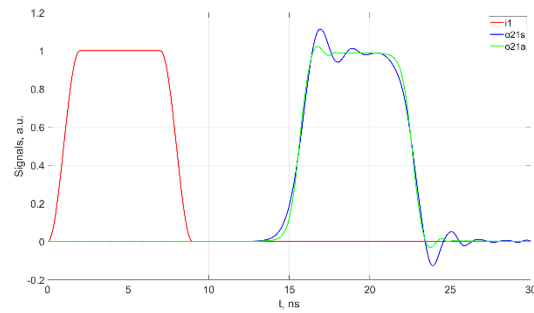

Figure 3: Input 2-5-2 ns (red) and calculated output signals in simple meander (blue) and one with separators (green).

Strip-coax Helix

The slow-wave structure based on a helical line formed by parallel short sections of a metal stripline connected in series by semi-rigid 50-Ω coaxial cables (UT250A) under the ground plate was developed at LANSCE in the 1980s [3] to chop a continuous 750-keV beam (β = 0.04); see Fig. 4. The coaxes work as delay lines. There are 97 periods of length 1.016 cm along the beamline; the strip length is 8.407 cm, width 0.7925 cm. The beam aperture is rather large, with half-gap h = 18 mm, but the deflecting efficiency is high, η = 0.96. The rise/fall times of the structure itself are about 2 ns; the pulser is much slower, ~7-10 ns.

Figure 4: LANSCE chopper: two helical structures are tapered out downstream. Coax cable connections are visible on the top plate; the strips can be seen at the bottom one.

Similar strip-coax structures can be used for LAMP MEBT chopper (with shorter strips and coaxes) or LEBT chopper (with much longer coaxes). Figure 5 shows a CST model of the strip-coax chopper structure adjusted for LAMP MEBT (β = 0.08).

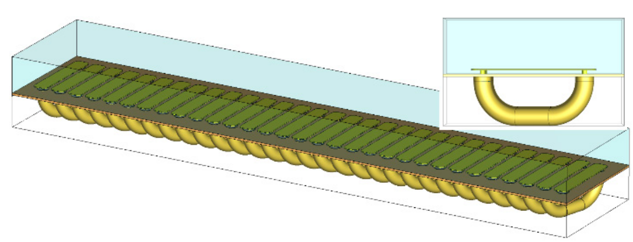

Figure 5: CST model of LAMP MEBT strip-coax chopper structure. Light-blue box shows half of chopper aperture.

The model has 30 periods of length 1.016 cm, with the strip length reduced to 4.45 cm. Even with half-gap h = 18 mm, the structure efficiency is high, η = 0.92. The calculated electric field produced by a voltage pulse 2-5-2 ns (cf. Fig. 3) is plotted in Fig. 6 at t = 11 ns from the pulse start.

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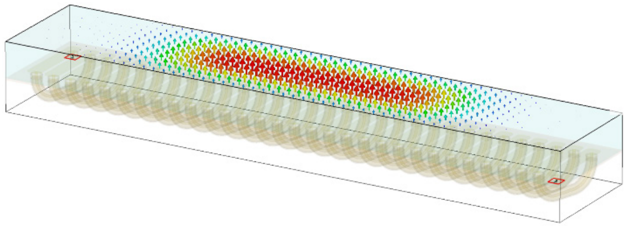

Figure 6: Electric field of 2-5-2-ns pulse in the beam plane of MEBT strip-coax chopper at 11 ns (unnormalized).

Dual helix

A 200-Ω dual-helix chopper structure was developed at FNAL [6] for 2.1-MeV beam (β = 0.067), see Fig. 7. The structure has risetime ~2.5 ns and high efficiency. The high line impedance makes it easier for the voltage pulser to provide high repetition rates of pulses. The helix parameters can be adjusted to β = 0.08 for the LAMP MEBT.

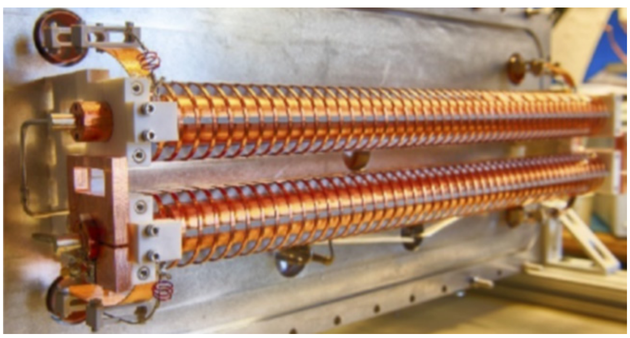

Figure 7: Dual-helix 200-Ω chopper structure, FNAL [6].

LEBT CHOPPERS

The beam velocity in the LEBT is very low, β = 0.0146 at 100 keV, while the chopper aperture is large, $2h$ = 4 cm. The estimated edge risetime is $t_e \approx 2h/\beta c \approx 9$ ns. Trying to design a structure with much shorter rise/fall times does not make much sense. Meander lines to match such a low velocity will be too wide, with strong strip coupling, and not very efficient, see in [10].

A model of the strip-coax structure adjusted for this beam energy is shown in Fig. 8. It consists of 40 strip-coax periods of length 7.5 mm along the beamline, with strips having a length 10 cm and width 5 mm. The coax connections become rather long to provide the required time delay to match the low beam velocity. The structure efficiency is η = 0.92. If we use the wider strips like in the LANSCE chopper, the structure will have 30 periods of length 1.016 cm and efficiency η = 0.95. However, the coax loops will be even longer in the vertical direction.

The structure CST modeling in time domain allows to estimate rise/fall times at about 5 ns. The calculated electric field produced by a long voltage pulse 7-21-7 ns is plotted in Fig. 9 at the time t = 50 ns from the start of the pulse.

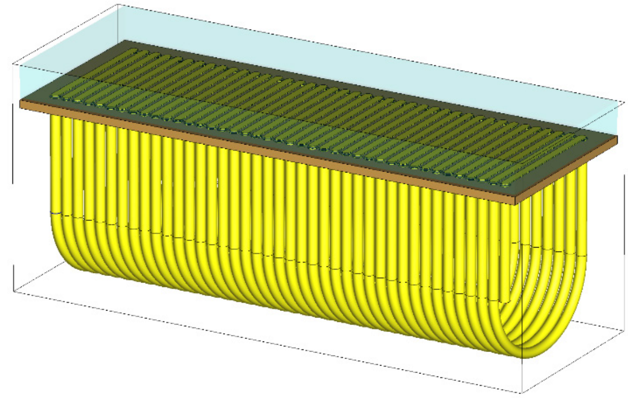

Figure 8: CST model of LAMP LEBT strip-coax chopper structure.

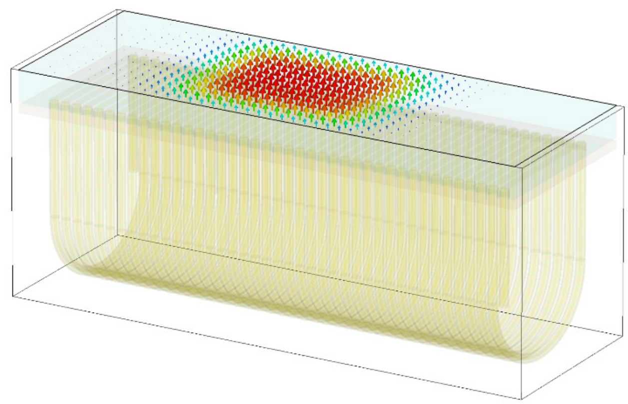

Figure 9: Electric field of a 7-21-7-ns pulse in the beam plane of LEBT strip-coax chopper at 50 ns (unnormalized).

CONCLUSION

We considered and compared a few types of traveling-wave current structures for LAMP choppers: strip-coax helix, meander-folded stripline on high-dielectric-constant substrate, and dual-helix structure. All of them can provide the required short rise / fall times. Structures based on meander-folded stripline on high-dielectric-constant [1, 5] substrate, while simple, have lower efficiency, which leads to higher required pulser voltages. Strip-coax structures pioneered in the LANSCE chopper [3] can be adjusted for both LAMP MEBT and LEBT choppers. They provide high efficiency and acceptable rise/fall times. The dual-helix structure developed at FNAL [6] can be adjusted for the LAMP MEBT. Its main advantage is 200-Ω line impedance that makes easier for the pulser to achieve high pulse repetition rates.

The MEBT pulser design remains challenging. This is caused not only by the required short rise/fall times, but also by the high voltage needed, and especially by the high pulse repetition rate.

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