REVIEW OF FAST BEAM CHOPPING

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Abstract

Several types of fast beam chopping systems in use or under construction are presented. Emphasis is given to their specific technologies and in particular their various fields of application. Important parameters are duty cycle, rise- and fall-time, ringing and overall bandwidth. Certain systems have very specific driver concepts, since the generation of multi-kW peak power with nanosecond transients, high repetition rate and very good pulse shape fidelity is not a trivial issue. The design of driver amplifier and actual chopper structure are not always mutually independent and thus some of the limiting aspects will be discussed.

INTRODUCTION

Over the recent years different chopper structures and chopper systems (e. g. RAL-ESS, LANL-SNS, JAERI CERN-SPL) have been designed and tested. Some of them are already in operation, others still under construction and / or in development. Many of these chopper structures contain slow wave deflectors, since the beam to be chopped has a fairly low momentum, usually with β = v/c values between 5 and 10 %. The specifications for the chopper systems differ largely in terms of duty cycle, rise-and fall-time as well as required deflection angle. Thus there is no unique solution for all existing machines and the structures and hardware presently available has been optimised for each individual application.

DISCUSSION OF CHOPPER CONCEPTS

In the following sections the properties and design concepts of the four chopper systems mentioned above will be shown and subsequently discussed. Obviously this selection cannot be complete and priority is deliberately given to the most recent projects.

THE RAL-ESS CHOPPING SCHEME[#]

This is an example of a chopping scheme for a next generation spallation neutron source [1]. Chopping is restricted to the 2.5 MeV medium energy beam transfer (MEBT) line, where a low level of emittance growth is predicted [2,5]. The proposed 'fast-slow' chopping technique addresses the requirements for a ~ 2 ns transition time, a 200 ns to 0.1 ms chopping duration, and a programmable duty cycle [2]. Components of the European Spallation Source (ESS) front-end are shown in schematic form in Fig. 1. ESS front-end specifications call for significant technical development and the design may be considered to be very relevant for next generation spallation sources and neutrino factories [3].

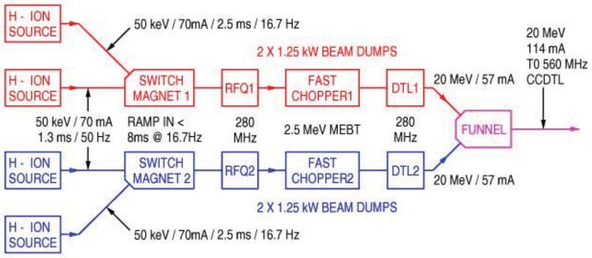

Figure 1: ESS front-end schematic [2].

A schematic drawing of the 2.5 MeV ESS MEBT line is shown in Fig. 2. and a corresponding table of key parameters can be found in [2].

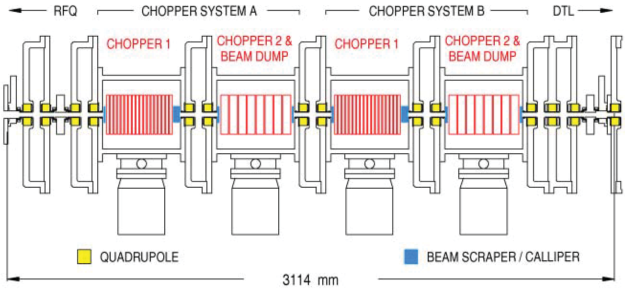

Figure 2: ESS MEBT line with 'Tandem' chopper [2].

The configuration has evolved from a previously reported design [4], and utilises two slow-wave E-field chopper systems operating in 'Tandem'. The design reduces beam dump power dissipation, and high voltage pulse generator repetition frequency by a factor of two, without incurring excessive emittance growth.

Simulated r.m.s beam radii and emittances from a revised optical design [5] return beam radii around 2 mm in both planes [2]. Input matching from the RFQ, use of regular lattice functions with the same beam aspect ratios in the channel cells, and a final six parameter output matching section, result in an acceptably low level of emittance growth and halo development. Optical amplification of beam deflection has not been attempted, and chopping fields are therefore higher than in other designs [6]. Key parameters and a timing schematic for one sub-system of the 'Tandem' chopper configuration are shown in Table 1, and Fig. 3, respectively.

'Tandem' sub-systems are identical in operation and operate alternately at a repetition frequency of 25 Hz. Each sub-system consists of an upstream fast chopper with a meander type slow-wave electrode structure [7]

[#] Supported by EC Research Infrastructure Activity FP6 "Structuring the European Research Area" program, CARE –RII3-CT-3003-506395 and a downstream (slower) main chopper (Fig. 3 top) with water-cooled lumped element electrodes, which also serve as a beam dump.

Table 1: Key parameters for the ESS chopper system [2]

	Prechopper	Chopper
Beam energy	2.5 MeV	
Chopping factor	30 % (ring stacking regime)	
Electrode voltage	± 2.2 kV	± 6.0 kV
Electrode length	340 mm	360 mm
Electrode gap	14 mm	11 mm
Deflection angle	16 mrad	66 mrad
Pulse transit. (10-90%)	~ 2 ns	~12 ns
Pulse duration	12 ns	240 ns-0.1 ms
Pulse repetition freq.	2.4 MHz	1.2 MHz
Burst duration	1.5 ms	
Load impedance	50 Ω	35 pF / 60 nH
Repetition rate	50 Hz (two systems @ 25 Hz)	
Beam power on dump	2.5 kW (2 systems @1.25 kW)	

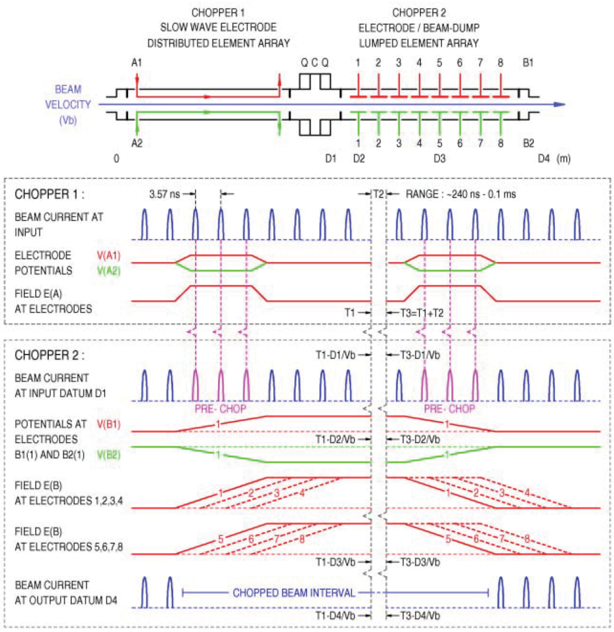

Figure 3: Two stage (fast-slow) chopping scheme [2].

Slow-wave chopper 1 produces a uni-polar pulsed field that deflects just three adjacent bunches through ~ 16 mrad. into scraper S2, S3 and chopper 2 beam dump electrodes, creating two ~ 14 ns duration gaps in the bunch train at the beginning and end of each chopped beam interval. These gaps ensure that no partially chopped bunches result from the slower field transition time of chopper 2.

Fig 4, and 5 shows 'General Particle Tracer' (GPT) [8] simulations of particle tracking with space charge for the cases of fast (pre-post) chopping, and main chopping, respectively. Eight pairs of adjustable scrapers control beam halo, beam displacement during fast chopping and function as diagnostic beam "callipers".

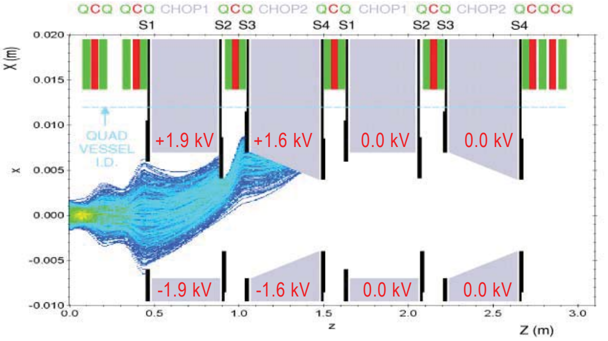

Figure 4: Fast chopping / Bunch 1-3 and 63-66 chopped.

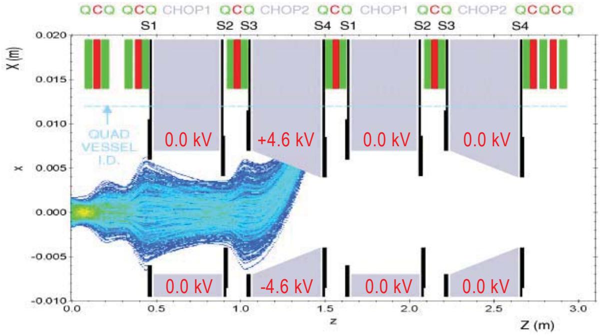

Figure 5: Slow chopping / Bunch 4-62 chopped.

THE LANL-SNS CHOPPING SCHEME

Structure (SNS-MEBT)

The MEBT chopper matches the deflecting electric wave velocity along the beam axis to the beam particle velocity, thus providing a rise and fall time determined mainly by the rise and fall times of the electric pulse. The parameters of this chopper are given in Table 2.

Table 2: SNS MEBT chopper parameters

Parameter	Value	Comments
Beam energy	2.5 MeV	β=0.073
Structure length	35 cm	
Meander width	96 mm	
Gap	18 mm	Adjustable
Pulser voltage	±2350 V	Max. ±2500V
Deflection angle	18 mrad	
Chopping period	945 ns	
Duty factor	32 %	Beam on:68 %
Structure rise/fall time	1.5 ns	
Pulser rise / fall time	10 ns	2-98 %

The current structure is based on the meander-folded notched strip-line with separators [9, 10, 11], see Fig. 6. The notched meander line provides the proper wave phase velocity along the beam path while keeping the characteristic impedance of the line equal to 50 Ω. The separators (metallic ridges situated between adjacent meander elements) reduce the strip-to-strip coupling and thus minimize the dispersion due to this mutual coupling.

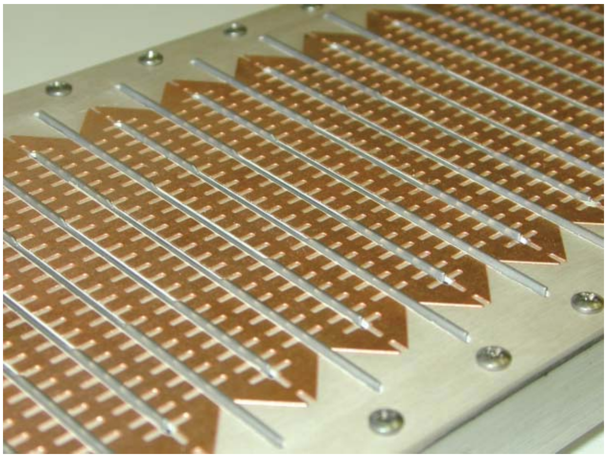

Figure 6: Close-up view of the notched-meander current structure [9].

Technology (SNS MEBT)

The notched meander line is supported by a T-shaped dielectric support that goes all along the strip-line length. The support is carved from a continuous dielectric plate of Rogers' duroid RT/6002 and afterwards the notched meander pattern is chemically etched on the copper coating of the dielectric plate. The copper thickness in the transmission line is 0.25 mm, and the dielectric is 2.5 mm thick. The metal width in the line is 8 mm, and the meander period is 1 cm; it leaves 2-mm gaps between the straight strips. The grounded metal separators protrude into these gaps through the narrow cuts in the dielectric. The notches on the line serve to slow down the TEM wave along the line straight sections to 0.68*c*. The notches are 3 mm deep and 1 mm wide, and their period is 4 mm. The whole structure is clamped by bolts near its sides to the metal ground plate, and the dielectric supports are glued to the ground plate with a special epoxy. The ground plates are fabricated of 6061-T6 aluminum alloy.

Pulser (SNS MEBT)

The chopper pulser has a peak voltage of 2.35 kV, higher by a factor 2.6 compared to its original specification of 900 V, so that the peak current through the meander line is about 47 A. It results in a power dissipation along the chopper structures of between 10-20 W. Active water cooling will be used. The original rise time requirement for the chopper system was set at below 2.5 ns, which led to the development of the fast current structure. Later beam dynamics simulations have shown that partially chopped bunches would not lead to extra beam loss in the SNS linac or the ring transfer line. The requirement for the pulser voltage was changed to 2.35 kV with a slower rise and fall time, below 10 ns, thus allowing up to 3 partially-chopped bunches in the beginning and at the end of each chopper pulse, which lasts around 300 ns. The pulser was developed by Directed Energy Inc. (Fort Collins, CO); it uses 4 FETs in series for each voltage source, positive and negative.

The SNS MEBT chopper system was tested with beam at ORNL in 2003. All the results satisfy the chopper system requirements [13].

LANSCE CHOPPER

The SNS travelling-wave chopper is based on the same principle as the strip-coax helical structure [12] successfully used at LANL for many years. The present chopper system at Los Alamos Neutron Science Center (LANSCE) was constructed for the Proton Storage Ring (PSR) in the early 80s. It works at beam energy of 750 keV and provides a rise time of approximately 7 ns with a larger contribution from the pulse modulator. The current structure itself is capable of providing a pulse front slightly longer than 2 ns, with an overshoot on the 10% level ringing for a few nanoseconds. This coax-plate structure is 1 m long and consists of two parallel plates each interfaced with many small strips. These are connected with coaxial cables on the reverse side of each plate to form a circuit that is continuous along the structure.

The LANSCE pulse modulator was developed in the early 80s as a fast vacuum-tube-driven device. In the 90s it has been revised to a solid-state model, which is easier to maintain at peak performance, but with a slower rise time. Both LANSCE pulsers give 500 V. The old pulser used 8 vacuum tubes in parallel; it was very fast (about 2.5 ns rise / fall "on a good day", typically 50% slower), but its tuning was fairly difficult. Its reliability was a serious issue, so it has been replaced later with a slower, but more reliable solid-state pulser.

THE J-PARC CHOPPER SYSTEM

The J-PARC linac has a two-stage chopping system with an LEBT pre-chopper and an MEBT chopper [14]. A. parameter list is given in Table 3. The LEBT pre-chopper is an energy modulation induction cavity, with which one can drive bunches beyond the longitudinal acceptance of the RFQ. The MEBT chopper is an RFD (RF deflection cavity) with short time-constant or low Q – value (around 10) driven by fast RF bursts from a high power RF amplifier. Bunches are kicked horizontally with the RFD and removed with a collector downstream. With the cavity modulating the LEBT beam energy, the downstream RFQ operates as an "energy filter" by letting the off-momentum beam arrive outside the momentum acceptance of the RFQ. The MEBT chopper has been tested, and, as shown in Fig. 7, the design rise/fall time of 10 ns has been achieved [15]. It has also been confirmed that the residual current during "chopper-on" periods is less than 10^{-4} of the nominal current (5 mA). Further testing of the chopper performance is now in progress during beam commissioning of the J-PARC linac front-end at KEK [16].

Table 3: Parameter list for the J-PARC chopper

Beam energy	3 MeV
Type	RFD
Operation frequency	324 MHz
Operation mode	TE11
Number of cavities	2
Number of gaps per cavity	1
Cavity length	172 mm
Bore radius	5 mm
Gap length	20 mm
Full rise / fall time	15 ns
Deflection field voltage	1.6 MV/m
Beam-on duty factor	56 %
RF power source type	Solid state amp.
Number of cavities per RF source	2
Peak RF power per cavity	30 kW

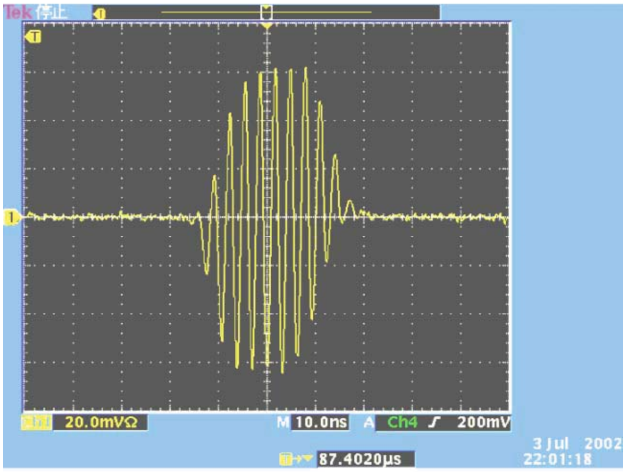

Figure 7: Waveform of a chopped beam obtained with a beam position monitor in MEBT. The horizontal scaling is 10ns/div. The pulse duration is shortened to demonstrate the chopper performance [16].

THE CERN-SPL CHOPPER*

The fast chopper for the CERN SPL (Super conducting Proton Linac) consists of a double meander structure with β = v/c of 0.08 printed on an alumina substrate for the deflecting plates. For the parameters see Table 4. Each chopper unit is 50 cm long and housed in a quadrupole magnet surrounding the vacuum chamber.

The deflecting plates are driven simultaneously in a dual mode of operation. For frequencies above about 10 MHz the travelling wave is used mode and below the quasi-electrostatic deflection. These structures are water-cooled to handle heating from beam losses as well as from the deflecting signal.

For the actual chopping structure a printed circuit design has been selected using a double meander type micro-strip line on a 3 mm thick alumina substrate (c.f. figure 8.). Details of the production process for this printed circuit are given in [16]. We used a MoMn layer (fired at 1500º C in an H_2/N_2 atmosphere) which has several layers of other metals added. It is given its final shape by a chemical etching process. Results of extensive numerical simulations as well as measurements on the rise- and fall-times and the deflecting efficiency have been presented in [18]. The main motivation for this kind of approach was to keep the actual chopper structure as short as possible and to obtain moderate requirements for the deflection voltage by taking advantage of beam-optics related deflection enhancements.

Table 4: Selected Parameter list for the SPL Chopper

Beam energy	3 MeV
Overall length	3.7 m
Number of chopper structures	2 inside quads
Number of quadrupoles	11
Chopper plate length	400+400 mm
Chopper plate distance	20 mm
Separation chopped/ un-chopped beam	15 mm
Chopper structure rise-and fall time	<2ns (10-90%)
Chopper voltage pulse (per plate)	500 V
Effective chopper voltage pulse	400 V
Max. chopper frequency	44 MHz
Pulse length	8-1700 ns
Max chopping factor (duty cycle)	40%
Repetition rate	1-50 Hz
Output transverse emittance (rms, norm)	0.27 π mm mrad with collimator
Chopper deflection angle	6.8 mrad

The dual mode operation for the deflecting plate has been selected in order to obtain an optimum combination of bandwidth, pulsing parameter variation range and power to be provided from the pulser. Note that nearly all the power delivered from the pulse generator has to be dissipated later in a load.

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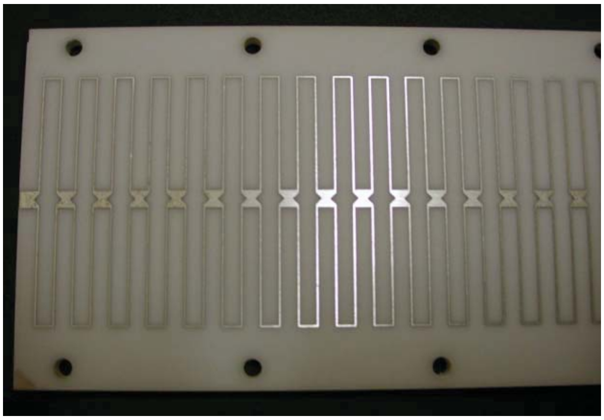

Figure 8: The alumina ceramic plates with printed meander structure (MoMn + 30 micron Ag); mounting holes for M2.5 screws are at the sides [17].

Thus the 50 Ohm termination travelling wave mode, essentially required for fast transients is only used above roughly 10 MHz and below the high impedance electrostatic deflection is used Details of these dual mode pulse amplifiers, which are presently under construction are given in [17].

Finally a 3D view of the complete chopper with its vacuum tank, water cooling system (beam loss related heating!) and triaxial feedthroughs is shown in Fig. 9.

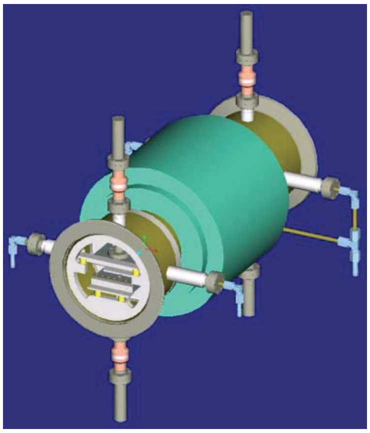

Figure 9: Complete chopper with vacuum tank mounted in a quadrupole [17].

CONCLUSIONS

Different concepts and ways of implementation for fast chopping structures have been shown and discussed. The main technological challenges for present developments are the pulse driver or power amplifier as well as the management of beam losses in the MEBT lines. Practical experience in the coming years will show which of the systems discussed above has the best performance and advances in solid state switching technology may lead to modifications in the deflector hardware.

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