OVERVIEW AND FUTURE DEMANDS OF FAST CHOPPERS

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Abstract

This talk will give an overview of current state-of-the-art and future demands of beam choppers with fast rise/fall time.

INTRODUCTION

The low energy portions of many existing and proposed high current hadron linear accelerators have a similar structure: an ion source, a low energy transport line (LEBT), an RFQ, a medium energy transport line (MEBT), and injection into a main linac. Often a certain temporal structure of the beam pulse is required. A typical example is a dividing the beam into single-turn segments for low-loss extraction from a circular accelerator, as shown in Fig.1 for the case of the SNS. This can be achieved by using a chopper, which consists of a kicker to deflect the unwanted part of the beam pulse off the axis, and a target to absorb the deflected beam. It is advantageous to place the chopper at a lower energy, where it is easier to deflect the beam and to manage the beam power deposited on the target. But, as we will show below, it is difficult to achieve a fast chopper rise time if the velocity of beam becomes too low. In practice the optimal location of a fast chopper is in the MEBT, where the beam energy is in the range of 2 to 5 MeV. In the following sections we will discuss the main MEBT chopper parameters, the primary design considerations, and several examples of MEBT chopper design in order of increasing difficulty: the operational SNS and JPARC choppers, the soon-to-be commissioned CERN Linac-4 chopper, and finally, the conceptual design of the future Project-X chopper. Since we will be discussing fast MEBT choppers exclusively, we will call them choppers for simplicity.

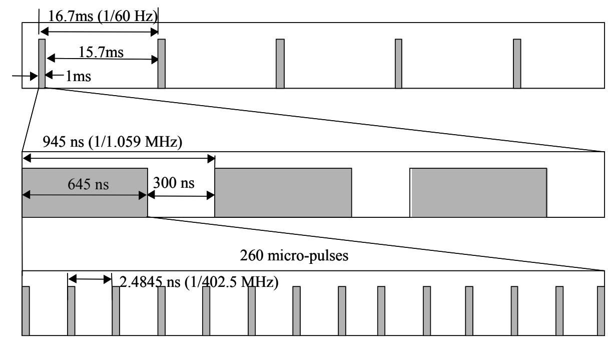

Figure 1: The SNS beam temporal structure: macro-pulse created by the ion source, mini-pulse formed by the chopper, and a micro-bunch structure created by the RFQ.

FAST CHOPPERS REQUIREMENTS

A good chopper has to provide a clean gap in the beam and a fast transition from the gap to full current. The first parameter is characterized by the extinction ratio, or the ratio of the beam current in the gap to the un-chopped beam current. The second parameter is characterized by the rise and fall time of the chopped pulses, which we will call the rise time, for simplicity. These two parameters are of high importance for the chopper kicker design, and will be the main focus of the following discussion.

The other important parameters are the chopping frequency and the duty factor. They define the beam power absorbed by the chopper target and the power requirements to the chopper power supply, i.e. the chopper driver.

Table 1: The Main Requirements for Several Modern Choppers

	SNS	J-PARC	Linac-4 /SPL	Project-X
Bunch frequency, separation	402.5 MHz 2.5 ns	324 MHz 3.1 ns	352.2 MHz 2.8 ns	162 MHz 6.2 ns
Rise time	<15 ns	10 ns	2 ns	2 ns
Chopping frequency	1 MHz	1.2 MHz	1 MHz / 44Mhz	162 MHz
Mini – pulse length	650 ns	455 ns	30 – 1700 ns /8-1700 ns	6.2 ns
Macro-pulse length, repetition rate	1 ms, 60Hz	0.5 ms, 25Hz	.6 ms, 1Hz / 50Hz	CW
Average beam power on chopper target	~ 100 W with pre-chopper	~ 100 W with pre-chopper	~40 W / 2000 W	> 20kW
Extinction ratio	$<10^{-4}$	$<10^{-4}$	$<10^{-3}$	$<10^{-4}$

The parameters of several modern MEBT choppers are shown in the Table 1. The required extinction ratio is in the range of 10^{-4} for all of them. The rise time is decreasing from ~15ns for the operational choppers to ~2ns for upcoming and future designs. The biggest difference is in the chopping frequency and the duty factor, which mostly affect the driver design and indirectly, through the achievable driver voltage, the overall design of the chopper.

CHOPPER EFFICIENCY

In order to be effective a chopper has to separate chopped and un-chopped slices of beam by a distance, which is large compared to the beam transverse size. We define chopping efficiency as $R = \frac{d}{\sigma}$, where d and σ are the separation and the beam size on the target respectively. The beam displacement on the target, for the case of a point kick, is

$$d = \sqrt{\beta_1 \beta_2} \sin(\Psi_{12}) \cdot \alpha , \qquad (1)$$

where β_1 and β_2 are the beta functions at the kicker and the target, respectively; Ψ_{12} is the betatron phase advance between the kicker and the target; α is the kicker deflection angle.

Substituting $\sigma = \sqrt{\beta_2 \varepsilon}$, where ε is the beam emittance, we obtain:

$$R = \sqrt{\frac{\beta_1}{\varepsilon}} \sin(\Psi_{12}) \cdot \alpha . \qquad (2)$$

The kicker deflection can be estimated as $\alpha = k \frac{V \cdot L}{\Delta}$, where k is a coefficient, V is the kicker voltage, and Δ is the gap between the kicker plates.

The kicker aperture should allow beam to pass through without significant losses therefore $\Delta = a\sigma = a\sqrt{\beta_1 \varepsilon}$, where $a \approx 5-10$ is a numerical coefficient that depends on the safety margin required. After substituting this to (2) we have for the chopping efficiency:

$$R = \frac{k}{a} \cdot \sin(\Psi_{12}) \cdot \frac{V \cdot L}{\varepsilon} \qquad (3)$$

The transport channel between the chopper and the target should be tuned such that $\Psi_{12} \approx 90^\circ$ in order to maximize the chopping efficiency. Then

$$R \approx \frac{k}{a} \cdot \frac{V \cdot L}{\varepsilon}, \qquad (4)$$

As one can see, the chopper efficiency is independent of the details of the transport channel. In the above treatment, for simplicity, we neglected the fact that the beta function for the deflected beam center of mass can differ from the beta function for the beam size calculation due to space-charge effect. That difference is not significant in practical cases and does not change the main conclusions.

The emittance in (4) is usually given; therefore only two parameters are left for maximizing the chopper efficiency: the kicker length and the driver voltage.

The driver voltage is limited by the capabilities of the available electronic components.

There are three factors limiting the kicker length.

The first one is a detrimental effect of long drifts on the beam dynamics. This effect is especially important for high peak current beams and sets a limit of ~.5m for an acceptable kicker length.

The second factor is the variation of the betatron phase along the kicker, which can be estimated as $\delta\Psi \propto \int \frac{ds}{\beta}$, from which follows that only part of the kicker of length $L \approx \beta_1$ is effective.

A possible solution is to divide one long kicker into several shorter ones, each of them placed at the optimal phase advance from the target. The equation (3) is valid for each kicker, therefore their kicks will add up if $\Psi_{12} \approx (2k+1) \cdot 90^\circ$ for every kicker.

And the last factor is the effect of kicker length on its rise time, discussed in the next chapter.

KICKER RISE TIME

The rise time of the field in the deflector depends on the high voltage power supply rise time, and the kicker structure bandwidth. Even if the field rises instantly, there will be a transient in the beam deflection due to the finite time of the beam propagation through the kicker. The transient time for an electrostatic deflector of length L is

$$\tau_f = \frac{L}{\beta_p c}, \qquad (5)$$

where $\beta_p \cdot c$ is the beam velocity.

In the case of a 3MeV ($\beta_p \approx .08$) beam the kicker length should not exceed ~25mm in order to keep the transient below 1ns. This serious limitation can be avoided by using a travelling wave kicker

The transient time of a beam deflected in a traveling wave deflector of length L is

$$\tau = \tau_f \cdot (1 \pm \frac{\beta_p}{\beta_w}) \quad , \qquad (6)$$

where $\beta_w \cdot c$ is the effective wave velocity. The negative sign corresponds to co-linear propagation of the beam and the wave, the positive sign to them moving in opposite directions. The transient time becomes zero when the effective wave velocity is equal to the beam velocity.

In a typical slow-wave kicker the electrical wave propagates along a longer path than beam so that the overlap region, where the beam and the wave paths cross, moves with the beam velocity. An example of such a structure is shown in Fig.2. The beam moves along the structure, and the wave moves across the beam through the beam-facing strip-lines and the coaxial delay-lines on the other side.

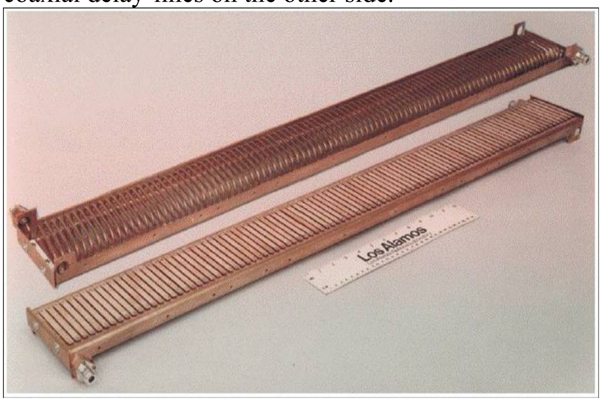

Figure 2: LANCE chopper structure: an example of a slow-wave transmission line.

The main drawbacks of slow-wave structures are the dispersion in the wave propagation, mainly due to coupling between the adjacent wave paths; and reduced kick strength due to gaps in beam-to-wave overlap regions.

It should be noted that formula (6) is only valid for an infinite travelling wave structure. The finite length kicker has an edge field, which is better described by an electrostatic field approximation (5) with effective length equal to the kicker aperture a. For that reason even an ideal slow-wave structure will have a transient time of $\tau \approx \frac{a}{\beta_p \cdot c}$, which sets a minimum beam energy required to achieve a certain transient time, i.e. ~1ns can be achieved in 20mm aperture if the beam energy is about 2MeV or higher. This is why the optimal location for a fast chopper is a MEBT.

EXAMPLES OF CHOPPER DESIGNS

SNS Chopper

The main parameters of the SNS chopper are given in Table 2, and a general layout is shown in Fig. 3 [2]. This is a classic arrangement of a kicker and a target, separated by a set of quadrupole lenses with 90º betatron phase advance.

Table 2: The Main Parameters of the SNS Chopper

Ion energy	2.5 MeV
Max Voltage	± 2.5 kV
Kicker gap	18 mm
Effective length	~370 mm
Max deflection	1.07 º
Time of flight	~ 17 ns
Power supply rise time	10 ns

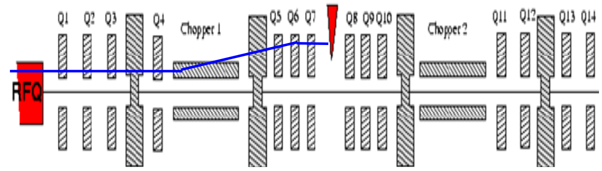

Figure 3: SNS MEBT and chopper layout.

The original kicker design was a slow wave transmission line made of a thin copper layer glued to a dielectric substrate as shown in Fig. 4. It demonstrated the design parameters in tests with low power beam but failed during high power operation [3] and was replaced with a simple strip-line kicker, which satisfies the operational requirements well [5].

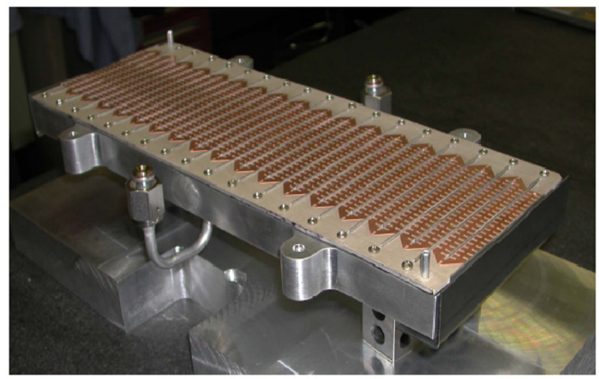

Figure 4: The original SNS chopper meander-line kicker.

JPARC Chopper

The main parameters of the JPARC chopper are given in Table 3, and a general layout is shown in Fig.5 [6]. This is again a classic arrangement of a kicker and a target, separated by a set of quadrupole lenses with 90º betatron phase advance.

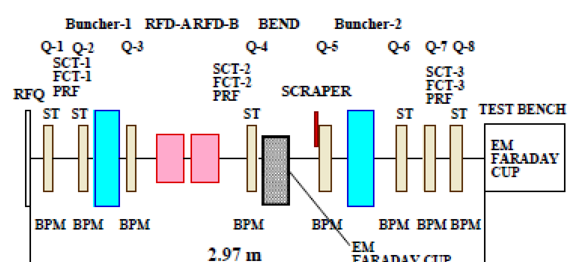

Figure 5: JPARC MEBT and chopper layout.

Table 3 : The Main Parameters of the JPARC Chopper

Ion energy	3 MeV
deflector type	RF cavity
aperture	10 mm
deflector length	2x170 mm
Max field	1.6 MV/m
Gap length	20mm

The difference with the SNS chopper is the kicker design, which is a two-gap TM RF cavity deflector. The RF cavity provides an enhancement of the deflecting electrical field by the cavity quality factor Q. The trade off is the corresponding increase in the field rise time. The optimized value of Q, whis is about 10 for the JPARC kicker(Fig.6,Tab.4), allows to satisfy the rise time requirements and to achieve a very high extinction ratio [6](Fig.7). This design is not optimal when the required rise time is comparable with the period of the micro-bunch structure as in the case of Linac-4 or Project-X.

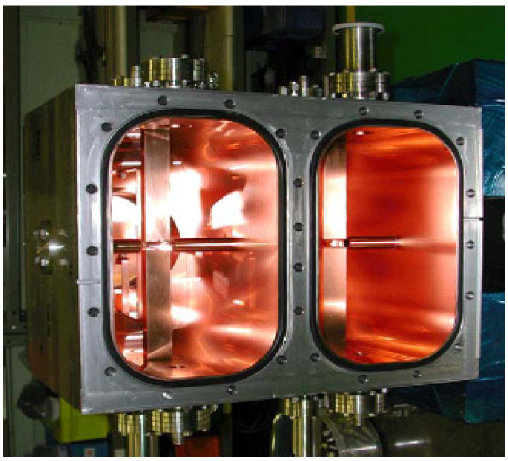

Figure 6: JPARC chopper RF kicker.

Table 4: The Main Parameters of the JPARC RF Kicker

frequency	324 MHz
Q	~10
Cavity rise time	10ns
Power amplifier	Solid state, 36kW
Amplifier rise time	15ns
Max field	1.6MV/m
Gap length	20mm

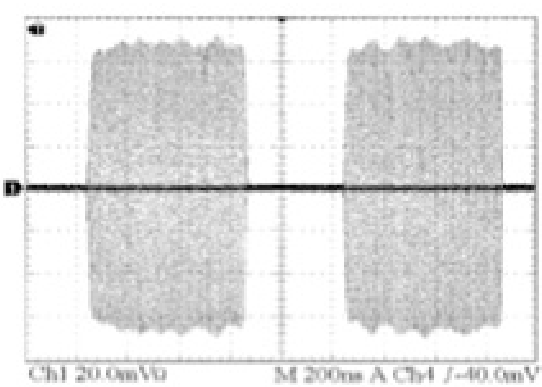

Figure 7: The chopped beam pattern produced by the JPARC chopper.

Linac-4 (SPL) chopper

The main parameters of the Linac-4 chopper are given in Table 5, and a general layout is shown in Fig.8 [7]. This is again a simple arrangement of a kicker and a target, separated by a set of quadrupole lenses with 90º betatron phase advance.

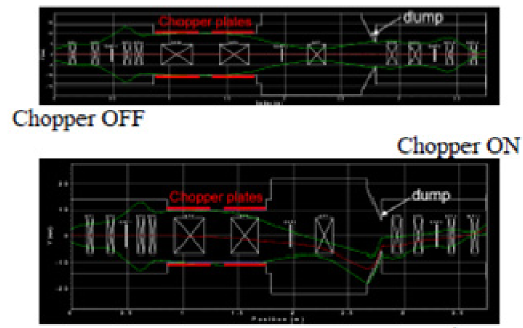

Figure 8: Linac-4 MEBT and chopper layout.

Table 5: The Main Parameters of the Linac-4 Chopper

Ion energy	3 MeV
Max Voltage	± 600 V
gap	20 mm
deflector length	2x400 mm
Max deflection	6 mrad
Power supply rise time	~2 ns

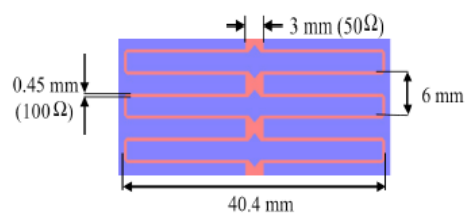

Figure 9: Geometry of the double meander line of the Linac-4 slow wave kicker.

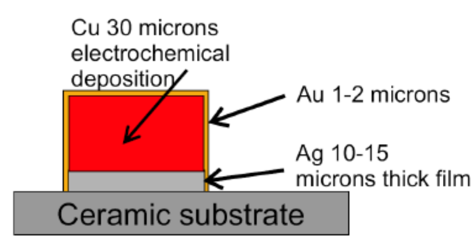

Figure 10: Layer structure of the double meander line of the Linac-4 slow wave kicker.

The novelty of the Linac-4 chopper is in the kicker design. The main idea was to increase the kicker length as much as possible. As we discussed in the previous section, beam dynamics with space charge does not allow for the long drifts required for placing long kickers. The proposed solution is to place the kicker inside the transport line quadrupoles, as shown in Fig.8. In order to fit inside a quadrupole magnet of a reasonable size the kicker has to have as narrow a profile as possible. To reduce the kicker width a slow wave transmission line on a high permeability ceramic substrate was developed. The details of the design are shown in Figs. 9, 10 and 11. This structure demonstrated the required rise time in the cold tests, as shown in Fig.12. Everybody is anxious to see how it will perform under high power beam conditions.

The intrinsic limitations of this design are a large dispersion in the dielectric, which limits the maximum length of the structure, and high resistive loss in the thin conducting traces, which limit the maximum duty-factor of the chopper. The last factor precludes the use of this design for the CW Project-X chopper.

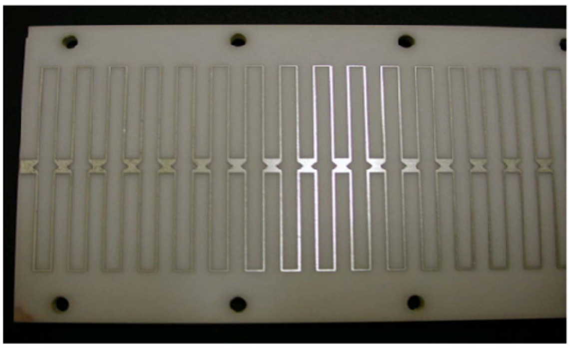

Figure 11: The slow wave structure of the Linac-4 chopper.

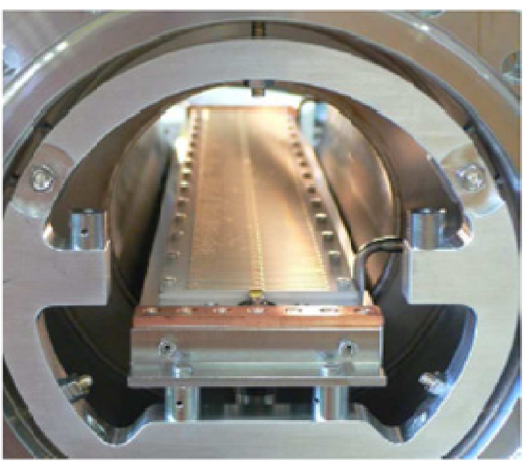

Figure 12: The kicker assembly of the Linac-4 chopper.

Project X chopper

The requirements for the Project-X chopper [8] represent a significant leap forward from what has been achieved with the existing technology. The required rise time of 2 ns is comparable to the Linac-4 parameters, but the chopping frequency of 162MHz and CW duty factor is a very difficult task for the chopper driver. The general understanding is that such parameters can be achieved only with relatively low voltage electronics, in the range of 150-300V. Equation (4) shows that a low voltage driver will require a correspondingly long kicker. The required length is so large that even the Linac-4 approach is not sufficient, because the betatron phase variation along the kicker becomes the dominant factor. A possible solution is to use a distributed system of shorter kickers with the proper phase advance as described in [1]. A preliminary design is presented in [9].

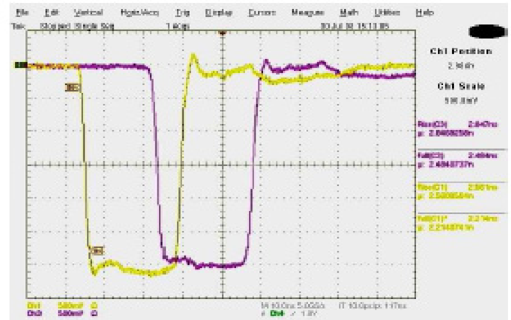

Figure 13: Measured Linac-4 kicker input and output waveforms. Yellow: chopper input, red: chopper output, 100 V/div, 10 ns/div.

CHOPPER DRIVERS

Designing a high voltage drivers for fast choppers is a significant technical challenge. Solid state components are used, almost exclusively, in modern drivers. The impedance of a large bandwidth kicker (50Ω usually) requires a high current source. This combination of high current, in the range of tens of amperes, and high voltage, from hundreds of volts to several kilovolts, can not be achieved by any single solid state device available today. Therefore multiple devices connected in series and in parallel have to be used. There is large number of possible driver topologies being developed by commercial vendors and in-house, good examples are given in [7, 10]. It is fair to say that the choice of chopper design is defined, in large part, by the parameters of the available driver.

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