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# Chopping Options for ESS

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## Introduction

To enable low injection beam loss and hence avoid machine activation, modern accelerators like SNS[1] and J-PARC[2] use low energy beam choppers to remove in a controlled way linac beam bunches that would otherwise fall outside the longitudinal stable region of the ring that follows. Future projects like Linac4 (now under construction at CERN)[3] and the ISIS upgrade linac[4] envisage similar beam chopping schemes for their linac front ends.

The ESS accelerator[5] proposed at Lund uses a 500 m long linac to deliver a 5 MW beam to the neutron target. Since no ring is involved in this long pulse option, low energy beam chopping is not as important as it is for the projects mentioned above. However, it has been suggested that chopping might still be necessary. The list below summarises the various possible uses for a chopper in ESS:

- The beam pulse from the ECR-type ion source will have a natural rise/fall time of tens of μs. It is likely that this segment of the beam (which will have very different space charge conditions) will be lost either in the RFQ or further downstream. A chopper might then be needed to control these possible losses.
- During beam commissioning, different beam modes will be required. A beam chopper could be useful in forming pulses as short as a few μs (a pilot pulse), tens of μs (diagnostics pulse) or hundred of μs (tuning pulse).
- For setting up the linac, beam line and target and for operational flexibility, various beam time structures will probably be necessary.
- It provides an in-built redundancy system for an emergency beam stop.

In this note, various beam chopping options for ESS will be summarised, based on already designed or operating systems.

## LEBT Chopping

### J-PARC

The J-PARC accelerator uses a two solenoid LEBT with a pre-chopper. The pre-chopper consists of an induction cavity similar to a beam transformer which can provide a small energy modulation[6]. The RFQ has a relatively narrow input energy acceptance, so by reducing the beam energy by ~10%, one can cut the RFQ transmission down to zero, thus using the cavity as a chopper and the RFQ vanes as beam dumps. For example, at J-PARC the nominal ion source energy can be set to 47.5 keV. For a

30 mA beam current the RFQ transmission threshold value is 43 keV, thus using the LEBT induction cavity to reduce the energy to <43 keV will completely remove the beam.

This arrangement has several advantages. It achieves relatively fast rise and fall times (less than 50 ns) and its short physical length (~10 cm) allows for a simplified overall LEBT design that can be optimised for maximum beam transmission. Additionally, the chopping duration can be adjusted by varying the voltage pulse length at the power supply, so that different beam pulse timing structures are in theory achievable.

However, even though the chopped beam energy is well below the threshold for neutron yield by copper activation, the effect of the beam bombarding the RFQ is not completely understood. Also the beam slice seeing the rising/falling cavity voltage (~50 ns at the beginning and the end of each pulse) requires special attention. It is quite possible that the some of the beam will be captured and accelerated by the RFQ, which could lead to potential losses further downstream and at higher energies, with more serious consequences.

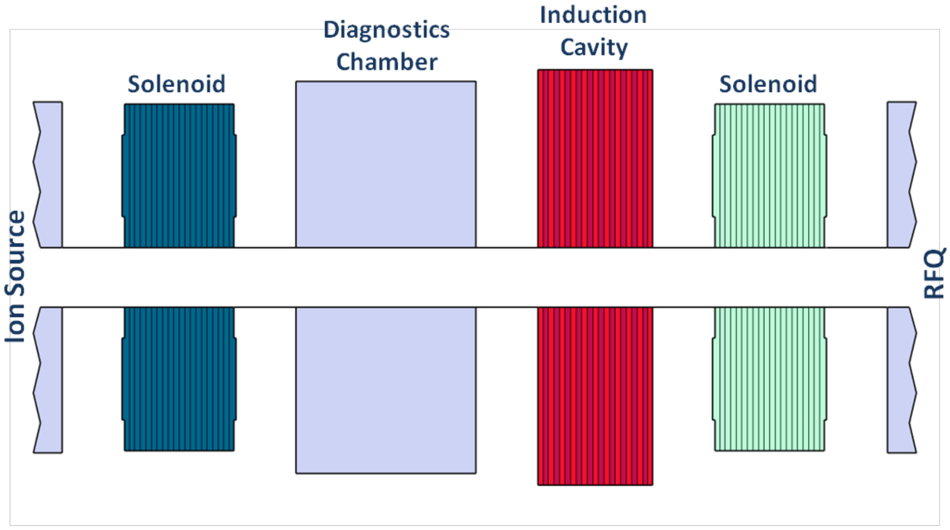


Figure 1: Schematic layout of the J-PARC LEBT line.

## SNS

The SNS LEBT consists of two electrostatic einzel lenses that transport and match a 65 keV H- beam from the ion source to the RFQ. The final LEBT electrode is divided azimuthally in four electrically isolated sections, each operating nominally at -40 kV to focus the beam into the RFQ. This electrode can also be operated as a beam chopper. By applying a +/-3 kV voltage on opposing segment pairs, the beam will be deflected onto a target. The overall length of the deflector is ~27 mm with transition times of <50 ns limited by the solid-state switches employed[7].

More recently, at SNS a two solenoid LEBT design has been proposed. It is aimed at improving the operational reliability of the present electrostatic LEBT. By using magnetic solenoids for focussing, the chopper electrodes will only be operated at potentials needed for chopping and steering (+/-3 kV) and as a result no high voltage will be required. Additionally, the new LEBT layout will be long enough to allow the characterisation of the beam before it enters the RFQ. The chopper design remains roughly similar[8].

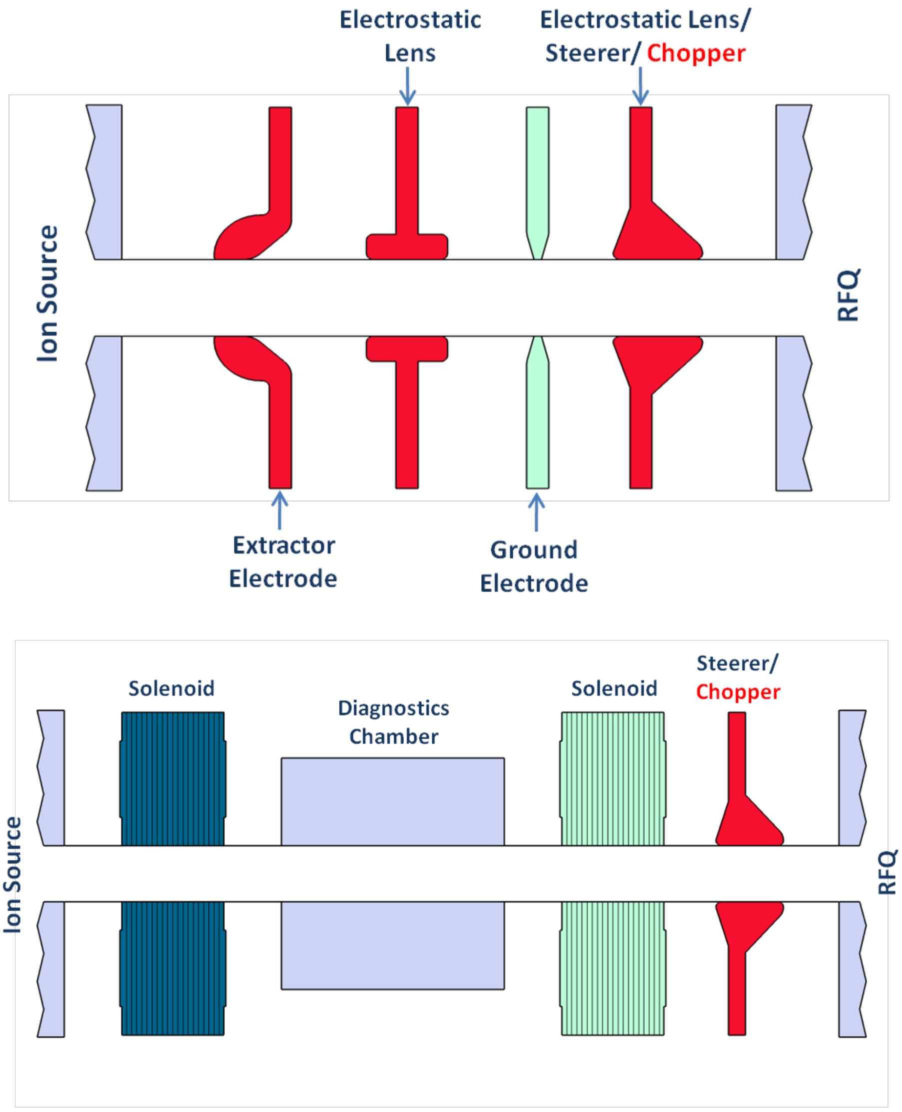


Figure 2: Schematic layout of the SNS LEBT line: existing (top) and proposed (bottom).

## CERN

The CERN Linac4 LEBT uses a two magnetic solenoid arrangement to transport the beam from the ion source to the RFQ. An electrostatic pre-chopper is placed between the two solenoids. It will be used to modulate the beam pulse length and cut the head and tail of the source beam, as the ion source will typically require more than 100 µs to stabilise. The chopper structure consists of two 10 cm long deflecting plates separated by a 10 cm gap. The pre-chopper will be capable of delivering voltages up to 20 kV, with rise/fall times under 2 µs. The transition time does not have to be much shorter, as up to 50 µs will be required for the space charge compensation to recover. The deflected beam will be dumped on the RFQ input flange, but the beam extinguishing factor is not 100 %.[9]

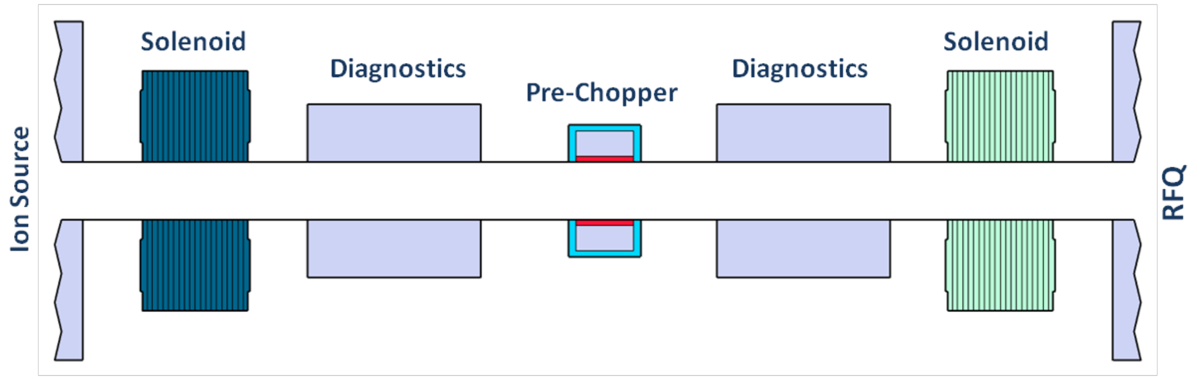


Figure 3: Schematic layout of the CERN Linac4 LEBT line.

It should be noted that the LEBT pre-choppers at CERN, J-PARC and SNS are designed to work in tandem with a fast MEBT chopper. This arrangement eases the load on the fast chopper, but also ensures that any partially chopped beam that passes through the RFQ is removed in the MEBT, thus eliminating the bunches that would otherwise be lost in the linac.

## MEBT Chopping

As mentioned above, because of the rise and fall times of the chopper voltage in the LEBT (tens of ns), the beam will contain partially chopped bunches. These bunches have a trajectory which is to some extent rather uncertain and are likely to be lost along the linac. To mitigate this effect, CERN, J-PARC and SNS combine the "slow" chopper in the LEBT with a fast MEBT chopper.

### SNS

The SNS MEBT matches and transports the beam from a 402.5 MHz RFQ to a DTL downstream. It uses an electrostatic fast chopper designed to partially remove the 2.5 MeV H- beam and it operates in tandem with the LEBT pre-chopper. The device itself consists of two ~35 cm long symmetric plates carrying the voltage pulse and separated by a 1.8 cm gap. To meet the rise time requirements, it is necessary to match the speed of the wave of the deflecting electric field along the beam axis to the particle velocity. To achieve this, the wave is sent along a meander-folded line. By travelling over a longer path, the wave phase velocity along the beam axis is reduced to that of the beam ($\beta$=0.073). The rise/fall time of the structure is ~1 ns. However, the limitation in reaching short chopper rise/fall times does not come from the transmission line structure, but from the 2.5 kV pulse generator which has a rise time of ~10 ns. As a result, just as at J-PARC, three bunches will be partially chopped, though simulations indicate that this will not lead to extra losses in the linac.[10, 11, 12, 13]

The chopper has been built and commissioned at SNS and although it met all the design specifications, it failed during high power operation. Uncontrolled beam loss and poor cooling capabilities caused the copper to overheat leading to severe structure damage. As a result, a more robust design has been adopted and the deflector has been modified with short strip lines connected by delay lines. The direction of the wave propagation is opposite to that of the beam and therefore the overall efficiency has been improved due to the magnetic field contribution. This has allowed a ~10% reduction in the power supply voltage.[14, 15]

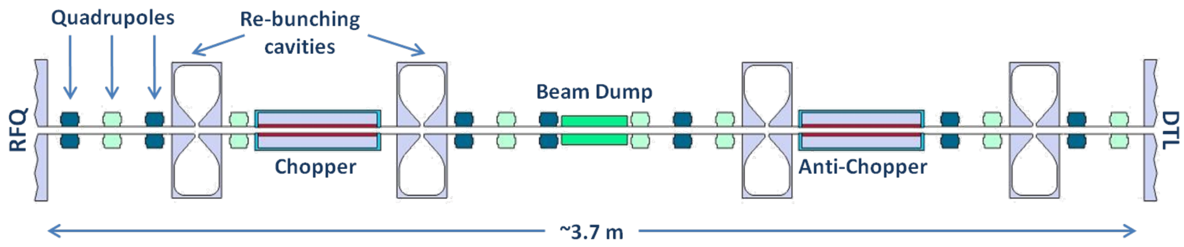


Figure 4: Schematic layout of the SNS MEBT line.

## CERN

A MEBT fast chopper is currently being commissioned for the CERN Linac4 project to be used in parallel with the LEBT chopper. It operates at 3 MeV and it consists of two units. Each unit is 50 cm long and houses the deflecting plates (40 cm). To reduce the total length of the line, the chopper units are designed to fit inside the bore of two MEBT quadrupoles which keep the beam focused in the chopping plane and to provide a 90 degree phase advance between the centre of the chopper and the beam dump. By placing the deflectors inside the quadrupoles, their length can be increased without compromising the beam dynamics. This in return minimises the required voltage between the chopper plates.

The design of the chopper structure is similar to the SNS chopper described above and it consists of a double-meander stripline matched to the beam velocity (β=0.08) and printed on an alumina substrate (better radiation hardness, heat transfer). The chopper driver is capable of delivering a maximum voltage of +/- 600 V and a rise time of ~2 ns. At a frequency of 352.2 MHz, the bunch separation is ~2.8 ns, meaning that bunch by bunch chopping will be possible. The maximum chopping frequency is 44 MHz, as required by some of the potential SPL applications.[16, 17]

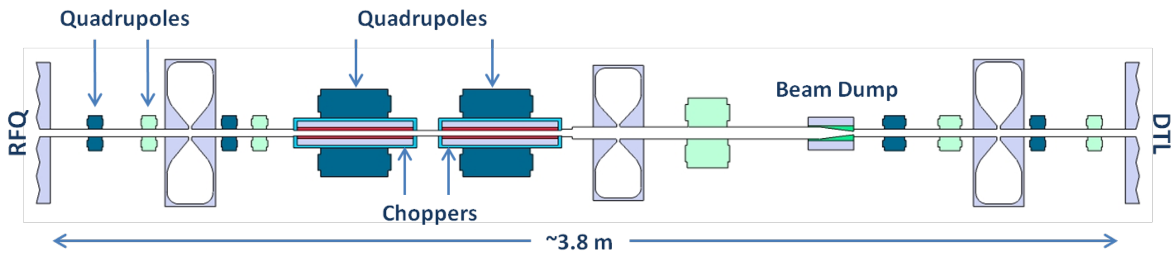


Figure 5: Schematic layout of the CERN Linac4 MEBT line.

## J-PARC

At J-PARC an RF chopper has been developed. The deflector consists of two RF cavities operated in a TE11 mode at 324 MHz. To save space in the MEBT, the two cavities have been constructed as a whole. Two electrodes are mounted in each cavity to concentrate the electric field and two beam pipes are added to shield the beam from the reverse deflecting effect of the magnetic field generated between the electrodes and the cavity walls. The transverse electric field oscillating between the electrodes deflects the beam away from the beam axis to a dedicated beam dump.

By lowering the loaded Q value of the cavity a fast rise time can be achieved. For a Q of 10, the measured rise time of the deflector system is about 27 ns, including a 15 ns contribution from the amplifier. However, by operating the RF cavities with a high driving power (36 kW), a chopped beam rise time of ~10 ns has been achieved. This is due to the fact that the deflecting field amplitude is sufficiently large before the RF pulse reaches the top plateau. By reducing the driving power by ~40 %, a good deflection was still observed, but the rise time has increased to ~15 ns.

The J-PARC RF deflector has the advantage of having a high deflecting field and a short rise time, which are the basic requirements for clean chopping. The experience at J-PARC suggests that the cavities are compact and easy to manufacture and the overall chopping system has so far proved reliable and flexible. However, bunch by bunch chopping is not possible with this scheme. Three adjacent bunches are only partially deflected during the chopper rise time. Nevertheless this has not proved to be a problem from a beam dynamics point of view. [18, 19]

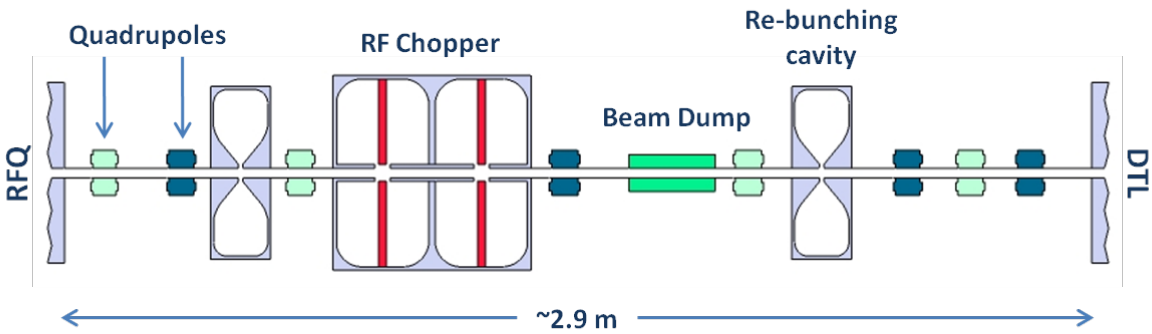


Figure 6: Schematic layout of the J-PARC MEBT line.

## RAL

For the 3 MeV Front End Test Stand project currently under construction at RAL, a novel chopping scheme is being proposed which does not make use of a low energy LEBT chopper. Instead, the MEBT optics have been optimised to accommodate two choppers: a fast transition time, short duration deflector (the fast chopper) and a slower transition time, longer duration deflector (the slow chopper). The fast chopper removes three adjacent bunches at the beginning and at the end of the chopping interval creating two gaps in the bunch train. These gaps will then be used by the second chopper field as a transition interval, thus preventing bunches being partially chopped during the transition interval of the second chopper.

The development of the electrode structures has been based on the existing SNS and CERN approaches described above, with the aim of achieving better mechanical and thermal stability as well as an improved coverage factor. A helical and a planar solution have been proposed. The helical transmission line consists of strip lines connected by coaxial cable delay lines. For the planar solution, the delay line is part of the strip line structure.

The fast pulse generator has a transition time of < 2ns, a pulse duration of up to 15 ns. The slow pulse generator has a 12 ns transition and a pulse duration of up to 100 µs. For perfect chopping, a voltage of ~+/-1.5 kV is necessary and a deflector length of ~45 cm for both slow and fast choppers.[20,21]

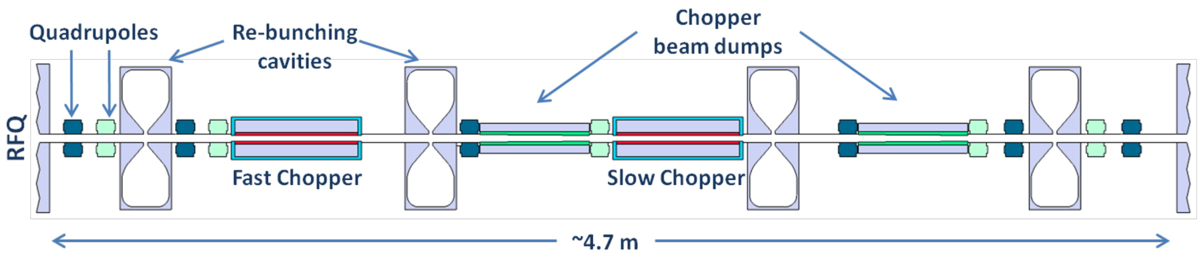


Figure 7: Schematic layout of the RAL FETS MEBT line.

## Conclusions

In this paper we analyse a number of beam choppers developed over the last decade for high intensity, high power pulsed proton linacs. It should be noted that this is not an exhaustive list, but rather a selection of relevant examples that can constitute a starting point for a customised ESS design.

A brief summary of the overall chopping scheme is given for each individual system, as well as deflector capability details. CERN, J-PARC and SNS have adopted a tandem approach with a slow pre-chopper in the LEBT and a MEBT fast chopper. At RAL, a MEBT only chopper is currently under construction.

While some of these systems could in theory be adapted to meet the ESS requirements, attention has to be given to several issues:

- The effect of the chopped LEBT beam bombarding the RFQ flanges.

- The trajectory of the partially chopped beam being captured by the RFQ.

- The change in the degree of space charge neutralisation by using a LEBT chopper.

- The consequences of having partially chopped bunches in the MEBT.

- Is operation using only the pre-chopper possible?

- Are there other means of beam shaping?

- End to end simulations.

In addition, a detailed analysis is needed to understand the effect on beam optics of having a chopper at all. The MEBT line is in particular challenging as relatively long beam line sections will be needed for the deflectors, thus limiting the overall MEBT capacity to control the emittance growth and beam loss.

Further details on fast chopping, including technical details on deflectors and pulse generators are given in a 2004 paper by F. Caspers[22] and a 2010 paper by A. Aleksandrov.[23]

**Table 1. LEBT and MEBT chopper parameters at CERN, J-PARC, RAL and SNS.**

| | CERN | | J-PARC | | SNS | | RAL |
|---|---|---|---|---|---|---|---|
| **Chopper Location** | LEBT | MEBT | LEBT | MEBT | LEBT | MEBT | MEBT Only |
| **Deflector Type** | Electro-static | Electro-static | Induction Cavity | RF Cavity | Electro-static | Electro-static | Electro-static |
| **Deflector Type Details** | Deflecting plate | Meander Stripline | Beam Transformer | TE11 Mode | Einzel Lens | Meander Stripline | Stripline with Coaxial/ Stripline Delay |
| **Beam Energy** | 45 keV | 3 MeV | ~50 keV | 3 MeV | 65 keV | 2.5 MeV | 3 MeV |
| **Beam Pulse Length** | 0.4 ms | | 0.5 ms | | 1 ms | | 2 ms |
| **Repetition Rate** | 50 Hz | | 25 Hz | | 60 Hz | | 50 Hz |
| **Bunch Frequency** | - | 352.2 MHz | - | 324 MHz | - | 402.5 MHz | 324 MHz |
| **Rise Time** | 2 µs | 2 ns | <50 ns | 10 ns | <50 ns | 10 ns | 2 ns |
| **Bunch by bunch chopping** | - | Yes | - | No | - | No | Yes |
| **Deflector Length** | 10 cm | 2*40 cm | 10 cm | 17.2 cm | 2.7 cm | 2* 35 cm | 2* 45 cm |
| **Deflecting Voltage/Field** | < 20 kV | +/- 600 V | +/-2.5 kV | 1.6 MV/m | +/- 3 kV | 2.5 kV | +/- 1.5 kV |

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