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DESIGN OF AN ELECTROSTATIC CHOPPER FOR THE NEW ISIS MEBT

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Abstract

The electrostatic chopper for the new ISIS medium-energy beam transport (MEBT) is a fast deflecting device to create gaps in the beam coming out of the RFQ, which will improve the trapping efficiency when injecting the beam into the ISIS synchrotron. Due to the stabilization time required by the ion source, it is expected that the first 100 µs of the 400 µs pulse need to be removed in order to deliver a clean flat top pulse to the synchrotron. The 300 µs pulse will then be burst-chopped into shorter pulses to reduce the losses at higher energies during the injection into the synchrotron at 50 Hz. The chopper must remove a maximum of 40% of the 300 µs pulse at the initial synchrotron frequency of 1.3 MHz. The deflected beam will be dumped into a beam dump inside the chopper device, while the remaining beam continues into the ISIS DTL. The chopper electrode dimensions were initially estimated from analytical calculations and from the beam dynamics simulations of the MEBT beamline. Electromagnetic (EM) simulations were developed to accurately estimate the field shape, the peak electric fields and the transient response of the chopper. Thermal calculations and a dimensional sensitivity study were also developed, but they are not presented here.

DESIGN PARAMETERS

The ISIS LINAC directly connects the RFQ to the first DTL tank at an energy of 665 keV. There is a desire to install a MEBT between both devices to improve the beam matching. The new MEBT consists of four Quarter Wave Resonators (QWR), a chopper and eight quadrupole magnets. The chopper is required to clean the leading edge of the H^- beam coming from the ion source and to burst-chop the beam into shorter pulses (Fig. 1), to reduce the losses at higher energies during the injection into the synchrotron.

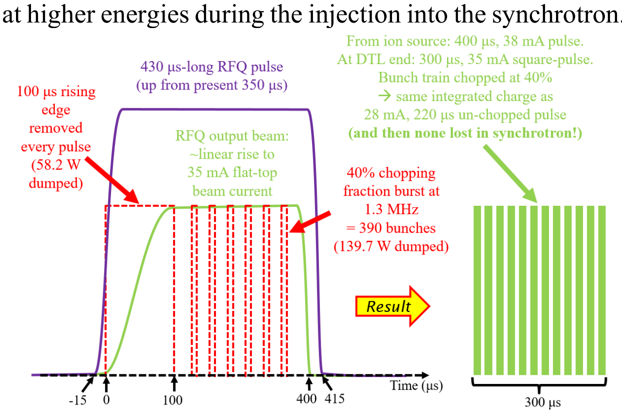

Figure 1: Beam chopping requirements.

It is possible to initially estimate the required voltage and field length by analytically solving the movement equation of an H^- particle in an electric field, so it hits the centre of the beam dump without hitting the electrode edges.

The particle path will be parabolic while inside the constant E field, and the defection angle of the velocity vector at the chopper exit can be defined as shown in Eq. (1).

$$\alpha = \tan^{-1}\left[\frac{q\,|\vec{E}|\,L}{\gamma\, m_o v_o^2}\right] \qquad (1)$$

where q is the electric charge, E is the electric field, L is the distance inside the field, γ is the relativistic Lorentz factor, m_o is the rest mass and v_o is the longitudinal speed.

The final electrode dimensions and required voltages were obtained from an iterative analytical and numerical calculation, to minimize the beam loss by optimizing the chopper positioning in the beamline and the beam waist. TRACE 3D was used for these initial simulations [1]. The chopper design specifications are shown in Table 1.

Table 1: Chopper Design Specifications

Parameter	Value	Units
Chopper type: Electrostatic (H bend)	N/A	N/A
Particle energy	665	keV
Beam current	35	mA
Minimum aperture	20	mm
Electrode length	160	mm
Electrode voltages	±7.5	kV
Integrated field homogeneity	< 3	%
Burst rate (during 300 µs each 20 ms)	1.3	MHz
Maximum pulse rise/fall time	16	ns
Max. flat top pulse duration (burst)	307	ns
Max. flat top pulse duration (50 Hz)	100	µs
Maximum flange to flange length	243	mm

The beam dump (designed as a simple tungsten wedge) was also positioned accordingly at a distance of 10 mm from the electrode end, and at 3.9 mm from the beam axis (adjustable during commissioning in 0.1 mm steps). The averaged dumped beam power coming from the removal of the beam leading edge is 58.2 W (0.5 x 35 mA x 665 keV x 100 µs / 20 ms). The maximum dumped beam power coming from the 300 µs burst chopping scheme is 139.7 W (40% x 35 mA x 665 keV x 300 µs / 20 ms). The total averaged beam power dumped during the nominal chopping process is therefore 197.9 W (Fig. 1).

GEOMETRY

The required vessel size around the electrodes was initially estimated by establishing the maximum electric fields allowable on the electrode corners and the effect of the grounded vessel on the system capacitances. The capacitance is important to keep the pulse rise/fall times within the specified 16 ns, as the HV switches have a transition time that depends on the load capacitance [2].

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The circuit capacitances in the simplified circuit of the chopper (Fig. 2, top) can be estimated from the vessel and electrode dimensions, and the circuit can be further simplified (Fig. 2, bottom) by assuming a perfect differential pulse synchronization in both electrodes (virtual ground between them).

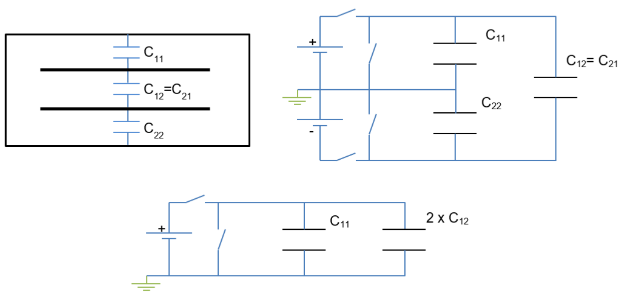

Figure 2: Simplified schematic of chopper capacitances.

A picture of the assembled chopper geometry used for simulations is shown in Fig. 3.

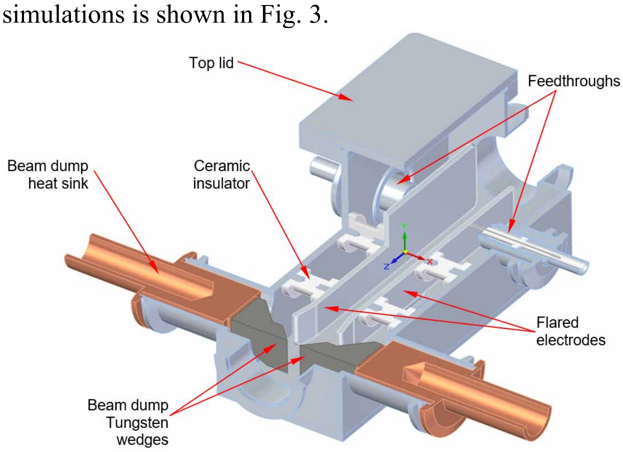

Figure 3: Chopper full geometry.

The selected feedthroughs were commercial (Allectra 250-SHV10), rated at 10 kV / 5 A DC, connected at the electrode ends due to mechanical restrictions. They are not constant impedance, which is not too problematic for this device as commented in the "Transient behaviour" section.

The electrodes were designed to reduce the peak electric fields at the corners and edges (3 mm radius) and they were made in 6063-T6 aluminium to improve the thermal conductivity. The electrode flared ends were designed to further reduce the beam loss during chopping. The extraction of the beam loss heat on the electrodes is critical, as they will only be cooled by conduction to the vessel through the ceramic insulators. Those were made of Shapal™, a machinable ceramic with a good thermal conductivity.

The beam dump tungsten wedge was bolted to a copper cylinder connected to a water cooling system. Two beam dumps were installed in the chopper to ensure that the full beam is never uncontrolledly dumped to the vacuum vessel. This also allows to alternatively send the beam to each of the beam dumps, to better spread the heat generation. In addition, as each HV switch requires a 100 ns recovery time between pulses, two dumps could allow for one switch to fire whilst the other recovers, thus permitting shorter pulses during the burst chopping mode.

ELECTROMAGNETIC SIMULATIONS

Electrostatic Analysis

The vacuum and other dielectrics shown in Fig. 3 were simulated in an electrostatic FEA model (Fig. 4) by using COMSOL Multiphysics [3]. The short flat top of the pulses allows for the use of an electrostatic model due to the large charge relaxation time constant in the insulators.

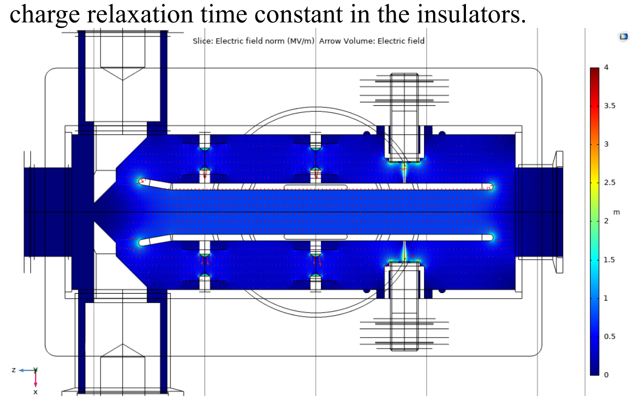

Figure 4: Electric field (MV/m) in the chopper @±7.5 kV.

The field inside the commercial feedthroughs has been excluded from Fig. 4 so it does not distort the scale of the fields. The fields everywhere were low enough to not to represent a risk in vacuum. A detailed zoom on the electrodes (Fig. 5) shows that the E field has a maximum of less than 3 MV/m at the rounded corners, which should guarantee an extremely small breakdown probability under a good vacuum, after careful surface finish and cleaning.

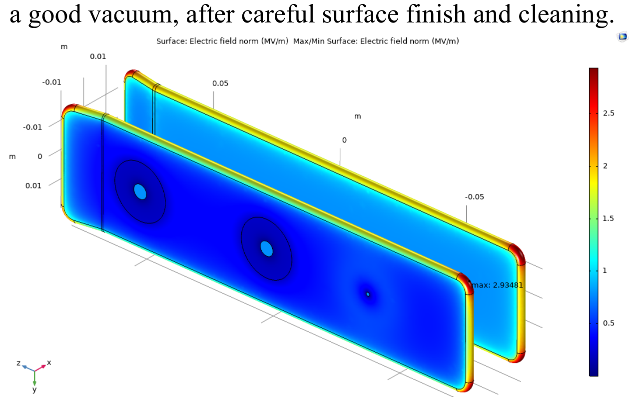

Figure 5: Electric field (MV/m) on the electrodes.

The circuit capacitances shown in Fig. 2 were calculated for two cases, one including the feedthroughs [Eq. (2)] and the other without them [Eq. (3)], so the result could be used also when modelling the feedthroughs as a transmission line with different characteristic impedance sections.

$$C_{w.\ feed.} = \begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} = \begin{pmatrix} 11.8 & 2.86 \\ 2.86 & 11.8 \end{pmatrix} \text{pF} \quad (2)$$

$$C_{w/o\ feed.} = \begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} = \begin{pmatrix} 8.25 & 2.86 \\ 2.86 & 8.25 \end{pmatrix} \text{pF} \quad (3)$$

The bespoke insulators required a detailed modelling of the small details in them, to ensure that the gaps at the end of the threaded holes were not experiencing too high electric fields [4].

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The transverse field $E_\perp$ in the aperture was integrated along the axis to obtain the transverse voltage (Eq. 4). The integrated field homogeneity could be estimated by calculating the transverse voltage at different integration lines on the surface of a 20 mm diameter cylinder coaxial with the chopper longitudinal axis. The transverse voltage varied between 125.46 kV and 121.59 kV, so the homogeneity of the field could be written as: 124.46 kV +0.8% -2.3%.

$$V_\perp = \int_{-\infty}^{\infty} E_\perp \cdot dl = 124.46 \text{ kV} \tag{4}$$

The electrostatic results were also used to trace a realistic 3D beam of particles through the chopper to check the aim at the beam dump and the scraping on the electrodes. The benefit of the bent electrodes is clearly shown in (Fig. 6). The Twiss parameters used at the chopper entrance were defined during the initial beam dynamics studies [1].

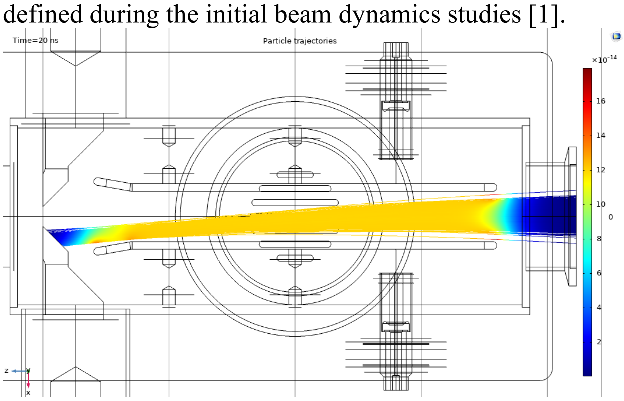

Figure 6: Particle trajectories for a realistic beam.

Transient Behaviour

The relative small electrical length of the chopper at the driving frequencies allows it to be considered as a lumped capacitor, and also for the feedthroughs to be connected to the electrodes at any position on their length. The voltage wave will be reflected back to the feeding transmission line in a constructive interference.

However, the switches require some time to close the circuit, creating a smooth rising edge for the voltage wave that injects a broad band of frequencies in the circuit. In addition, the impedance mismatch in the feedthrough (and/or cables) create resonating waves that bounce between the transmission lines. To deal with these dynamic effects in an inherently unmatched system, it is important to limit the length of the transmission lines by locating the power supply as close as possible to the feedthroughs (ideally just on the feedthroughs). It is also important to design the internal transition between the feedthrough and the electrode to limit the naked pin inductance [5] in series with the circuit, which could lead to more resonances.

An equivalent circuit was developed to estimate the dynamic behaviour of the chopper (Fig. 7, top). The transmission lines in the circuit represent the feedthrough with a variable characteristic impedance, calculated from the feedthrough geometry and materials. The pair of switches have smoothly varying impedances during the ON and OFF events to better represent the voltage rising edge.

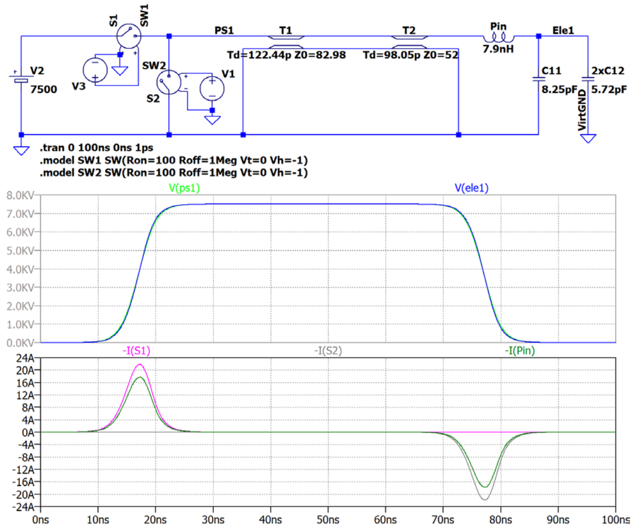

Figure 7: Chopper equivalent circuit (top) and voltage and current waves (bottom) to simulate dynamic effects.

The resulting voltage and current waveforms during one chopping event (Fig. 7 bottom) show that there are no ringing effects (slightly overdamped system) and there is no overshoot on the rising edge, which confirms that the chopper can be driven at the required speeds. A full 3D FEA transient model developed in COMSOL Multiphysics confirmed these results with good accuracy.

The integrated energy flowing on each of the charging/discharging events in Fig. 7 is 487.3 μJ (no surface losses considered). The number of chopping events every 20 ms is 390 (Fig. 1), plus one additional chopping event to remove the beam rising edge. That results in 391 x 50 = 19550 pulses per second. As each pulse involves a charge and a discharge event, that is equivalent to a maximum averaged 19550 x 2 x 487.3x10^{-6} = 19 W, fully dissipated if the power supply does not recover any energy between charge/discharge events.

It is also possible to roughly estimate the power loss in the feedthrough pin (where the specific loss is highest due to the high H field) by using the current pulse that flows through it (Fig. 7 bottom). For each of the frequencies in the pulse, it is possible to calculate the skin depth. The RF losses can then be calculated at each single frequency and then added together. The averaged power loss for the feedthrough pin due to the transmission of the EM waves was 52 mW, while the total power dissipated inside the other chopper elements (electrodes, vessel, etc.) was estimated to be negligible [4].

CONCLUSION

The electromagnetic design of an electrostatic chopper for the new ISIS MEBT has been presented, including the estimated beam loss and the electrostatic and transient simulations. The dimensions and shape of the chopper components have been defined to fulfil the requirements for the field strength, switching speed and breakdown probability.

The thermomechanical and the sensitivity analyses will be presented elsewhere. The mechanical model and drawings are ready and the manufacturing is almost finished.

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REFERENCES

[1] S. Lawrie *et al.*, "A pre-injector upgrade for ISIS, including a medium energy beam transport line and an RF-driven H− ion source", in *Proceedings of the 18th International Conference on Ion Sources*, Lanzhou, China, Sep. 2019.

[2] Behlke, "FSWP High-Voltage Push-Pull Pulser", `https://www.belke.com/pdf/datasheets/fswp_instructions_v1.pdf`

[3] COMSOL AB, "COMSOL Multiphysics® software", `https://www.comsol.com`

[4] I. Rodriguez, "Chopper for the ISIS MEBT – Technical Design Report", Rutherford Appleton Laboratory, UK, Sep. 2020.

[5] F. W. Grover, *Inductance Calculations*. New York, NY, USA: Dover Publications, 1973.