

WORKING CONCEPT OF 12.5 kW TUNING DUMP AT ESS

Y. Lee*, A. Olsson, M. Eshraqi, R. Miyamoto, M. Möller, T. Shea, C. Thomas, M. Wilborgsson
S. Ghatnekar Nilsson, S. Molloy, Y. Levinsen, European Spallation Source ERIC, Lund, Sweden
F. Sordo, ESS-Bilbao, Bilbao, Spain

Abstract

The linac system at the European Spallation Source (ESS) will deliver 2 GeV protons at 5 MW beam power. The accelerated protons from the linac will be transported to the rotating tungsten target by two bending magnets. A tuning beam dump will be provided at the end of the linac, downstream of the first bending magnet. This tuning dump shall be able to handle at least 12.5 kW of beam power. In this paper, we present the working concept of the tuning dump. The impact of the proton beam induced material damage on the operational loads and service lifetime of the tuning dump is analysed. A number of particle transport and finite-element simulations are performed for the tuning beam modes.

INTRODUCTION

The ESS linac accelerates the protons from the ion source up to 2 GeV in a sequence of normal conducting and superconducting accelerating structures. The project scope of the full beam current is 62.5 mA at 5 MW time-averaged beam power. The beam is pulsed with 4% duty factor, 2.86 ms pulse length at 14 Hz repetition rate. The accelerated beam will be delivered to the target by two dogleg bending magnets during neutron production for the materials research. During the beam study and early start up phases, the dogleg magnets will be turned off and the beam will be sent to the beam dump for tuning purposes. Figure 1 shows the schematics of the ESS linac [1]. There are two commissioning phases of the high- β beam, which are aligned with the cryomodule installation plan of the ESS linac [2].

The tuning dump shall stop the tuning beams with a design beam power rating of 12.5 kW. It shall be shielded, following ESS General Safety Objectives [3]. The design lifetime of the tuning dump is 40 years, but there must be a remote handling path that enables the change of it in case of its accidental failure.

TUNING BEAM MODES

There are four tuning beam modes used for the commissioning, study and early start-up of the ESS linac [4].

Probe Mode

The lowest power probe beam is used to perform the very first check of the linac machine configuration. The pulse length is kept below 5 μ s to limit the maximum accidental beam loss in the linac components. Low energy probe beams will be stopped by temporary beam stops most of the times, where the last beam stop is installed in the first half of the medium- β . For any energies beyond 500 MeV, the probe

beam will be sent to the tuning dump. The repetition rate of the probe beam is 1 Hz.

Fast Tuning Mode

After a successful commissioning of the probe mode, the repetition rate will be increased up to 14 Hz. Phase scans will be made to rapidly determine and verify the RF set-points. The beam energies above 200 MeV will be tuned on the tuning beam dump. To limit the beam loading in the RF cavities, the peak pulse lengths will be kept below 5 μ s. The full current of 62.5 mA and the maximum repetition rate of 14 Hz can be attempted.

Slow Tuning Mode

In this tuning mode, the pulse length will be increased up to 50 μ s. This provides good quality signals to invasive proton beam instrumentation devices such as wire scanners, and allows the calibration of the non-invasive measurement devices. The slow tuning mode is also used to diagnose and monitor the low-level RF feed-backs and feed-forwards, and onset of beam loading. It enables more precise single-pulse measurements as well. The beam energies above 200 MeV will be tuned on the tuning dump. The maximum beam repetition rate is limited by the time averaged beam power of 12.5 kW, which the tuning dump is designed to handle.

Long Pulse Mode

The full beam current of 62.5 mA and the full pulse length of 2.86 ms will be attempted on the tuning dump. This beam mode is only used when the linac is reasonably tuned during the slow tuning mode. The pulse length will be slowly increased in few steps, and the RF feed-forward tables will be populated and used accordingly. The beam loading and Lorentz force detuning compensation, as well as other long term effects will be verified. The full pulse beam will be tuned for low beam losses. The maximum beam repetition rate is limited by the time averaged beam power of 12.5 kW on the dump. Successfully tuned, the beam is ready to be sent to the target either for beam on target study or spallation neutron production.

THERMO-MECHANICAL ANALYSES

Model Studied

The tuning dump for the ESS linac is a bulk cylinder made of CuCr1Zr [5]. The CuCr1Zr is a precipitation hardened alloy for high temperature applications where material need to have a combination of high thermal conductivity and mechanical properties. The onset point of materials softening

* yongjoong.lee@ess.se

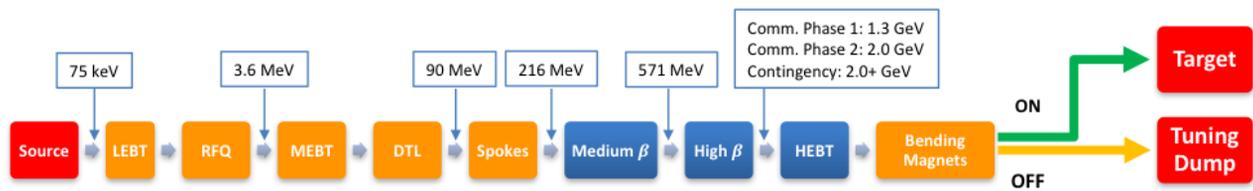


Figure 1: The schematics of the ESS linac.

is about 400 °C. The cylindrical dump core is 50 cm in diameter and 170 cm in length. The dump core is surrounded by steel and concrete shielding. Lacking the possibility of passive cooling with natural heat convection, there is a 130 cm high vertical heat conduction path made of copper connected to the dump core. The top of the copper column is cooled by water to remove the heat deposited in the dump.

For thermal analyses, only the dump core is modelled for axisymmetric and 3D simulations. The heat flux from the dump core to the cooling water surface on top of the copper column is modelled by the wall heat transfer coefficient $\alpha_{\text{core}} = 70 \text{ W/m}^2/\text{K}$ on the cylindrical surface. This value of α_{core} is obtained by analysing the heat transfer from the dump core to the water cooling surface area on top of the copper column.

Beam Footprint on Tuning Dump

The nominal beam footprint on the tuning dump is given by $\sigma_x \times \sigma_y = 16 \times 25 \text{ mm}^2$. To verify the working concept of the tuning dump, the axisymmetric beam footprint $\sigma_x \times \sigma_y = 16 \times 16 \text{ mm}^2$ is used for most of the presented thermal and mechanical analyses. This beam footprint represents a reasonably conservative case with 56% higher beam intensity than the nominal one, and allows quasi-2D axisymmetric simulation setup.

For the thermo-mechanical analyses, the beam cases listed in Table 1 have been studied, for the nominal and axisymmetric beam footprints. Each of the five chosen beam energies respectively represents the beam commissioned up to DTL, Spokes, Medium- β , High- β Stage 1, and High- β Stage 2.

Table 1: Studied Tuning Beam Parameters

Tuning Mode	Ener. [MeV]	Curr. [mA]	Pulse [μs]	Rep. [Hz]	Pow. [kW]
Probe	90	6.25	5	14	0.04
	220	6.25	5	14	0.09
& Fast Tun.	570	62.5	5	14	2.49
	1300	62.5	5	14	5.69
	2000	62.5	5	14	8.75
Slow Tun.	570	62.5	50	7	12.5
	1300	62.5	50	3	12.2
	2000	62.5	50	2	12.5
Long Pulse	570	62.5	2857	1/10	10.2
	1300	62.5	2857	1/20	11.6
	2000	62.5	2857	1/30	11.9

Temperature, Thermal Stress and Fatigue

The heat deposition in the tuning beam is calculated by FLUKA [6, 7], and the calculated volumetric heat deposition is used for the thermal simulations.

The transient and steady temperatures in the tuning dump are calculated for the beam cases listed in Table 1, using ANSYS® Multiphysics™ software. The calculations show that the tuning dump is most heavily loaded in the "Long Pulse Mode", when a full current and full pulse length beam is attempted on it. Table 2 summarises the calculated maximum temperatures in the dump, for the "Long Pulse" beams with the axisymmetric beam footprint $\sigma_x \times \sigma_y = 16 \times 16 \text{ mm}^2$. The transient peak temperature in the dump is shown in Fig. 2, for a 2 GeV tuning beam at full pulse and full current, where the initial condition is set by steady state thermal configuration. Note that the temperatures are well below the material softening set-off temperature 400 °C of CuCr1Zr.

Table 2: Calculated maximum temperatures for the beam footprint $\sigma_x \times \sigma_y = 16 \times 16 \text{ mm}^2$.

Energy [MeV]	Max. Temp. Steady	Max. Temp. Pre-pulse	Max. Temp. Post-pulse
570	208 °C	194 °C	250 °C
1300	188 °C	177 °C	239 °C
2000	181 °C	170 °C	240 °C

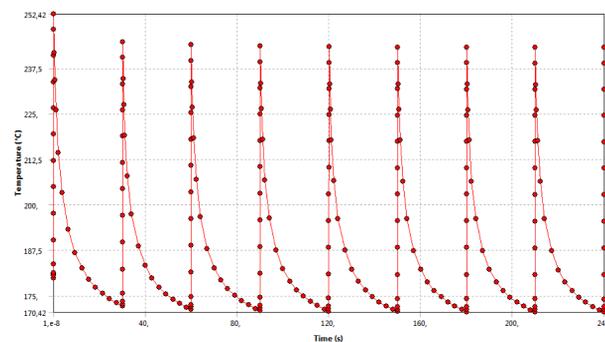


Figure 2: The transient peak temperature in the dump.

The case with the nominal beam footprint $\sigma_x \times \sigma_y = 16 \times 25$ is studied using a full 3D model. For the 2 GeV beam at full current and full pulse length, the calculated peak steady state temperature in the dump is 132 °C, which is 50 °C lower than the axisymmetric beam case. The calculated

peak temperature at the pulse peak is 180 °C, which is well below the material softening set-off temperature 400 °C.

The transient mechanical stress is calculated for the "Long Pulse Mode", using ANSYS® Multiphysics™ software. Table 3 summarises the calculated maximum von Mises stress for the temperature cases presented in Table 2.

Table 3: Calculated maximum von Mises stress for the beam footprint $\sigma_x \times \sigma_y = 16 \times 16 \text{ mm}^2$.

Energy [MeV]	Max. Str. Post-pulse	Max. Str. Range
570	101 MPa	70 MPa
1300	106 MPa	86 MPa
2000	122 MPa	106 MPa

The nominal beam case is studied using a full 3D model. The calculated maximum transient von Mises stress at the pulse peak is 96 MPa with the stress range of 82 MPa.

The fatigue characteristics of different CuCr1Zr are studied in Ref. [8]. Both unirradiated and irradiated specimens are tested at 22 °C and at 300 °C, with displacement damages up to 0.33 dpa. The measured fatigue limit is set by a stress amplitude of about 200 MPa. The calculated maximum stresses and stress amplitudes during pulse in the dump is well below this fatigue limit.

High Intensity Beam Handling Capability

During linac tuning, focused beam pulses with a high beam intensity can be delivered to the tuning dump. This can happen either due to a premature linac configuration or by an operational error.

In the probe and fast tuning modes, the 90 MeV beam provides the most severe beam loads to the dump due to its sharp Bragg peak near to the dump surface. The simulations show that the tuning dump can handle 90 MeV probe beam up to the maximum charge density of 10 $\mu\text{C}/\text{cm}^2/\text{pulse}$. For reference, when a 90 MeV beam with a 14 Hz repetition rate and the full 62.5 mA beam current is focused on the dump with a beam RMS size of 1 mm, the dump can sustain the maximum pulse length of 10 μs .

In the slow tuning mode, the 2 GeV beam case poses the greatest challenge. For the 2 GeV beam in the slow tuning mode with 50 μs pulse length and 2 Hz repetition rate, the tuning dump can take maximum current density of at least 1 A/cm^2 . This is equivalent to a beam RMS size of 1 mm.

In the long pulse mode with full current and full pulse length, the dump can take up to 16 mA/cm^2 beam current density, which is equivalent to a beam RMS size of 8 mm.

In order to estimate the worst possible beam intensity on the dump, error analyses of cavities and quadrupoles in HEBT and DMPL are made. The study has been made in the envelop mode with a conservative assumption that all the quads have a random error of up to 5 %, and the last cavity which is being tuned has a field error of up to $\pm 100\%$ and a phase error of up to $\pm 90^\circ$. The errors are

randomly distributed and 100 linacs per case are studied. The smallest beam RMS size obtained is larger than 5 mm. This indicates that the tuning dump will be able to handle most of the beams in the probe, fast tuning and slow tuning modes. During long pulse mode, it must be made sure that the beam is moderately expanded at least to the RMS size of 8 mm.

High Power Beam Handling Capability

To check the limit of the dump in taking high power beams, two cases have been studied for the axisymmetric beam with the footprint $\sigma_x \times \sigma_y = 16 \times 16 \text{ mm}^2$.

For a 2 GeV beam with time averaged beam power of 5 MW is sent to the cold dump at 14 Hz repetition rate, the calculated maximum temperature and peak stress in the dump are below the material softening set-off point and the yield strength respectively, up to four consecutive pulses. After 1 second with 14 beam pulses on the dump, the peak temperature and stress respectively increases to 800 °C and 1000 MPa. For such single event, the dump will undergo a plastic deformation but not a structural failure.

For a 2 GeV tuning beam at full current and full pulse length, the maximum repetition rate that the tuning dump can take is calculated to be 1/15 Hz. Once the beam is moderately expanded, this 24 kW beam can be sent to the dump during the start up phase, as far as adequate radiation shielding to the workers is provided.

EFFECT OF RADIATION DAMAGE

The 5 MW steady-state operation of the ESS linac will start in 2026, where 552 hours of beam study is planned per year [2]. Assuming that 2 GeV beam is constantly tuned at the dump at 12.5 kW beam power, the tuning dump will get a maximum displacement damage of 0.05 dpa per year, or 2 dpa during the entire facility lifetime of 40 years. The electrical resistivity of the dump core may increase up to 10% at 2 dpa, extrapolating the result presented in Ref. [9] for copper. This may correspond to maximum 10% loss of thermal conductivity in the dump core, assuming Wiedeman-Franz law. To evaluate the radiation damage effect in the dump core, thermo-mechanical simulations have been performed with a uniform 10% reduction in the thermal conductivity of CuCr1Zr. For the axisymmetric beam with an RMS size of 16 mm, the 10% degradation of thermal conductivity results in only 2% higher maximum temperature and almost equivalent stress range.

CONCLUSION

The proposed dump concept can manage the beams in different tuning modes that are defined for the study and commissioning of the ESS linac. While the dump shielding is designed for 12.5 kW, the studied concept can take up to 24 kW time averaged beam power without structural deformation. The design will be further optimised and detailed towards manufacturing drawings.

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