DYNAMIC RESPONSE OF SPALLATION VOLUME TO BEAM RASTER ON THE EUROPEAN SPALLATION SOURCE TARGET

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Abstract

To achieve a desirably low beam intensity on the target, the European Spallation Source (ESS) adopted a beam raster system at the high beta beam transport part of the linac. The raster system paints the beam on the target with frequencies up to 40 kHz within the 2.86 ms beam pulse, to form a uniformly expanded beam footprint. While the beam raster reduces the time-averaged beam current density to a level that the 5 years of design lifetime of the target system can be achieved with a high operational reliability, it could potentially induce deleterious dynamic excitations in the spallation volume made of tungsten. The stress wavelets created by raster sweeps can be amplified if the sweep frequency is in tune with a resonance mode of the tungsten volume. This coherent interference of the wavelets could lead to a high dynamic stress in tungsten, posing a risk of premature failure of the target. In this paper, the dynamic response of the spallation volume of the ESS target to different beam raster frequencies has been analysed, using multi-physics simulations based on measured material data. Finally, a safe operational range of the beam raster frequency band is proposed.

INTRODUCTION

A 5 MW class high power target station is under construction at the European Spallation Source (ESS) in Lund, Sweden [1]. The spallation target receives a 2 GeV proton beam with 2.86 ms pulse length and 14 Hz repetition rate. The proton beam with a nominal beam size of $\sigma_x \times \sigma_y = 13.5 \times 5.05$ mm^2 rapidly sweeps over a quasi-rectangular area $\Delta x \times \Delta y = 120 \times 40$ mm^2 on the target, instead of being uniformly expanded by nonlinear magnet system [2]. Specifically, the raster magnet system generates a Lissajous-like pattern using triangular wave forms to create a two-dimensional mesh of interweaved sweep trajectories. During the beam pulse, the trajectory of the beam centroid in the plane perpendicular to the beam direction on the beam entrance window of the target is described by

$$\hat{x}_i(t) = \frac{\Delta_i}{2}\left[4\left| \mod\left(\frac{n_i t}{\tau} - \phi_i, 1\right) - \frac{1}{2}\right| - 1\right], \quad (1)$$

for $i = x,\ y$, where τ is the beam pulse length and ϕ_is are free parameters representing phase shifts. The parameters n_x and n_y are the number of sweeps during the beam pulse respectively in the horizontal and vertical directions. These are correlated to the raster frequency f_i via $f_i = \tau / n_i$. The current design values for the raster frequencies are $f_x = 39.55$ kHz ($n_x = 113$) and $f_y = 29.05$ kHz ($n_y = 83$).

The spallation volume of the target consists of 6696 tungsten bricks which are separated by 2 mm wide helium coolant flow channels to each other. Each brick is of a same size, $L_x \times L_y \times L_z = 10 \times 80 \times 30$ mm^3. The surface spanned by L_x and L_y faces the impinging beam. For the design raster frequencies, each tungsten is hit by the beam centroid for 1 μs per each raster sweep, which is a typical pulse length of many short pulse spallation sources. Each micro-pulse deposits 125 J energy on the target, and it excites a dynamic stress wavelet in tungsten bricks. The stress wavelets coherently interfere with each other if the sweep frequency is in tune with a resonance mode of the tungsten brick. When it happens, the amplified stress waves may lead to an excessively high dynamic stress in tungsten, which could potentially cause premature failure of the target.

Resonance modes of a tungsten brick have been calculated, using ANSYS Multiphysics Modal Analysis [3]. There is a resonance mode at 78.7 kHz at 20 °C, which is close to twice the design value of $f_x = 39.55$ kHz. Note that the tungsten brick standing in the raster centroid receives the raster kick with twice the raster frequency, which is 79.1 kHz. This is only by 0.5% off from the resonance frequency identified. To date, engineering analyses of the ESS target have been based on quasi-steady time averaged beam raster profile. The proximity of the design raster frequency to a resonance mode necessitates the study of dynamic response of the spallation volume to fast transient beam raster.

RESONANCE MODES IN TIME DOMAIN

Beam raster induced coherent stress wave excitation modes in a tungsten brick subject to a maximum beam intensity have been studied in time domain, for the horizontal raster sweep numbers from $n_x = 100$ ($f_x = 35.00$ kHz) to $n_x = 131$ ($f_x = 45.85$ kHz), with fixed $n_y = 83$.

Beam Energy Deposition and Temperature Profile

To calculate the proton energy deposition in tungsten, a particle transport simulation has been performed using FLUKA [4,5]. The maximum differential energy deposition in tungsten by a single 2 GeV proton is calculated to be $dE/dz = 68.3$ MeV·cm^{-1}. The corresponding volumetric heat deposition in a tungsten brick during beam pulse is

$$q(t,x,y) = \frac{I_\mathrm{p}}{2\pi\sigma_x\sigma_y}\frac{dE}{dz}\exp\left[-\frac{1}{2}\sum_{i=1}^{2}\frac{\tilde{x}_i(t)^2}{\sigma_i^2}\right], \quad (2)$$

$$\tilde{x}_i(t) \equiv x_i - \hat{x}_i(t) - x_\mathrm{W}, \quad (3)$$

where $I_\mathrm{p} = 62.5$ mA is the proton beam current and x_W is the horizontal coordinate of the tungsten brick off the beam raster centroid $x = 0$.

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For the transient volumetric heat deposition in a tungsten brick, transient thermal simulations have been performed for a single pulse, using the ANSYS Multiphysics CFD (CFX) [3]. The rapid raster sweeps heat up the beam intercepting region almost uniformly from 300 K to 400.35 K during a single pulse. In order to capture the fast transient temperature change induced by the beam raster, a small time step size of $\Delta t = 0.12$ μs is used.

Dynamic Interference of Stress Wavelets

The calculated transient temperature configurations have been used as inputs for the ANSYS Multiphysics Transient Structural [3], to simulate how generated stress wavelets by the beam raster sweeps interfere with each other. Figure 1 shows the simulated post-pulse von Mises stress in a tungsten brick standing at the raster centroid, for the horizontal raster sweep rate $n_x = 112$ ($f_x = 39.2$ kHz). The tungsten brick received the raster kicks with a frequency of 79.1 kHz, which is quite close to the calculated resonance mode at 78.7 kHz. The simulation shows that a resonating longitudinal vibration mode in the beam direction is excited, where the maximum stress occurs at the centre of gravity.

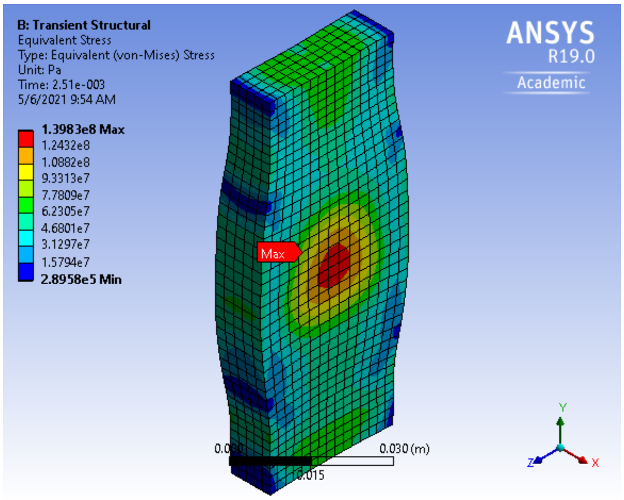

Figure 1: Simulated post-pulse temperature profile in a tungsten brick standing at the beam raster centroid.

Figure 2 shows the time dependent maximum von-Mises stress for the case of $f_x = 39.2$ kHz during a single beam pulse. The post-pulse transient stress reaches 158 MPa which is well above the quasi-steady stress 49.5 MPa. This clearly shows coherent interference between the wavelets generated by the beam raster. The higher post-pulse dynamic stress may shorten the fatigue lifetime of the tungsten bricks, compared to a quasi-steady value on which current design is based. Considering that tungsten loses its ductility and fracture toughness with increasing radiation damage [6], the higher dynamic stress will make the tungsten bricks more susceptible to an embrittlement failure.

The transient stress responses to different raster frequencies have been calculated. Figure 3 shows the maximum post-pulse von Mises stress for different horizontal raster sweep rates. The baseline is set at 49.5 MPa, which is the maximum post-pulse von Mises stress obtained from a quasi-steady structural analysis. Note that the post-pulse stress for the design raster sweep rate $n_x = 113$ is adjacent to the resonance peak at $n_x = 112$. The maximum von Mises stress is 34% higher at $n_x = 113$ than the quasi-steady case, which should be of a concern. There are incoherent modes between the resonance peaks. The dynamic stresses of these modes are still at least 4% higher than those of the quasi-steady cases. A conservative estimate of the bandwidth of each resonance peak is about $\Delta n_x \simeq 2$, whereas the average separation between the neighbouring peaks is about 5.

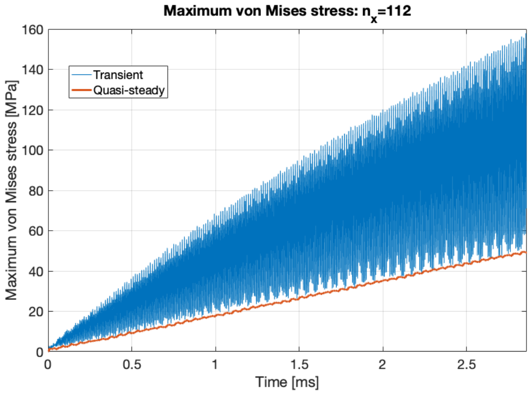

Figure 2: Time development of the maximum von-Mises stress for the case of $f_x = 39.2$ kHz, which is then compared with a quasi-static stress response.

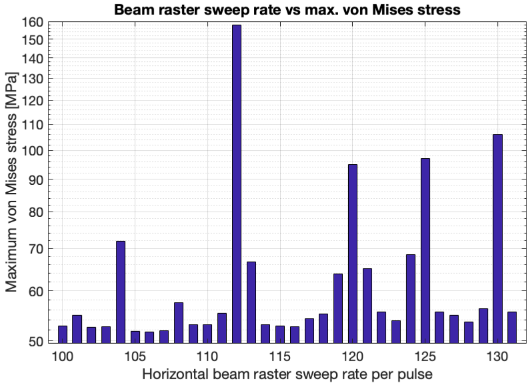

Figure 3: Maximum post-pulse von Mises stress for different horizontal raster sweep rates.

The resonance frequency depends on Young's modulus, Poisson's ratio and density. While the variance in Poisson's ratio is small for tungsten, Young's modulus and the density varies depending on tungsten grades, detailed manufacturing process and temperature. The longitudinal and transversal stress waves travel in solids with speeds given by

$$c_L = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}}, \quad c_T = c_L\sqrt{\frac{1-2\nu}{2(1-\nu)}}, \tag{4}$$

where E is the elastic modulus, ν is Poisson's ratio and ρ is the density of tungsten. The resonance frequency is proportional to the wave velocity c,

$$f_{R;N} = \frac{Nc}{2\Delta L}, \tag{5}$$

where N is the mode number and ΔL is the dimension in the wave propagation direction. The differential variances of E and ρ respectively to δE and $\delta\rho$ result in the differential variance of the resonance frequency,

$$\frac{\delta f_R}{f_R} = \frac{1}{2}\left(\frac{\delta E}{E} - \frac{\delta\rho}{\rho}\right). \tag{6}$$

Given the densely populated resonance modes shown in Fig. 3 and considering that uncertainties in resonance frequencies largely depend on uncertainties in materials data, it is important to know the density, elastic modulus and Poisson's ratio of the ESS spallation material with a high certainty, to determine safe operational windows for the beam raster parameters. For this purpose, a number of impulse excitation tests have been made at the UK Atomic Energy Authority (UKAEA) [7], to measure the density and the elastic modulus of the tungsten raw material used for the ESS target in the temperature range from 20 °C to 500 °C. The 500 °C is the maximum operational temperature of the tungsten bricks at 5 MW beam power. The simulations presented in this paper are based on the data so obtained.

From the differential changes in Young's modulus and the density to the temperature change from 20 °C to 500 °C, the differential change in resonance frequency $\delta f_R/f_R = -0.02$ is derived from Eq. (6). From Fig. 3, taking the resonance peak bandwidth $\Delta n_x \simeq 2$ and the differential change in resonance frequencies over the operational temperature range into account, we propose a safe operational domain of the horizontal beam raster cycles per pulse,

$$114 \le n_x \le 116 \quad \text{or} \quad 39.9\ \text{kHz} \le f_x \le 40.6\ \text{kHz}. \tag{7}$$

This requires a small adjustment of the current raster magnet setup, which is set to $n_x = 113$ ($f_x = 39.55$ Hz).

Effects of Horizontal Offset from Raster Centroid

The effect of horizontal location of a tungsten brick relative to the raster centroid has been studied. Figure 4 shows the calculated maximum post-pulse von Mises stress values for different horizontal offset positions, for selected raster sweep rates $n_x = 111$, 112 and 113. The peak at n_x decreases with increasing horizontal tungsten position offset. This is due to the increasing difference in raster sweep intervals between the forward and backward moves, with increasing position offset from the raster centroid. Note that target wheel rotation causes a horizontal position offset of 9 mm during a single pulse. The effect of the target rotation on the change in dynamic response of a tungsten brick subject to the raster sweep rates $n_x = 112$ and $n_x = 131$ are calculated for a tungsten brick standing at the raster centroid position. The inclusion of the rotation effects resulted in less than 1% change in post-pulse maximum stresses, not qualitatively affecting the dynamic behaviour of the tungsten bricks to beam raster.

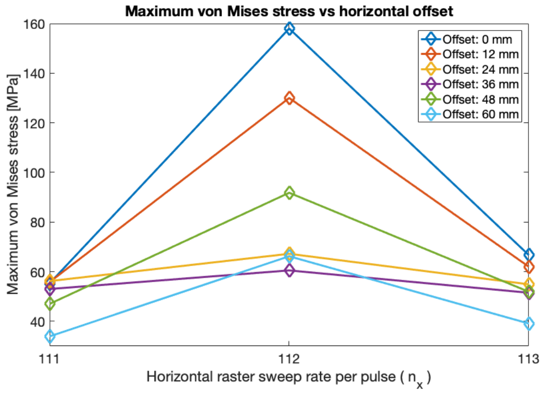

Figure 4: Maximum post-pulse von Mises stress values for different offset positions of tungsten bricks from the raster centroid, for $n_x = 111$, 112 and 113.

CONCLUSIONS

Dynamic responses of the tungsten bricks in the ESS target to the proton beam raster have been studied. Multiphysics simulations based on measured material data have been used for the study presented. A safe operational beam raster frequency band has been proposed, in which coherent interference of the wavelets generated by the beam raster sweeps are suppressed, avoiding potential detrimental dynamic vibration of the spallation volume in the ESS target.

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