Solid target studies in the UK

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An account is given of the latest plans to measure the thermal shock and fatigue in the proposed solid tantalum target for a neutrino factory.

1. INTRODUCTION

The proposed target \([1,2]\) for the neutrino factory is a rotating tantalum toroid operating at a temperature of \(\sim2000\) K to dissipate 1 MW of power produced by the impact of a 4 MW proton beam. Alternatives to the toroid are being considered - such as firing individual target bars through the beam or passing a “chain” of bars through the beam.

The UK programme \([3]\) of target developments is centred on the study of thermal shock and the long term fatigue effects. Initially the shock was to be created in the laboratory by impacting a projectile onto a hot tantalum sample, but this does not properly replicate the conditions that will be produced in the target. It was then proposed to do in-beam tests but access to a suitable proton beam has proved difficult. It is now proposed to pass a high current electric pulse through a thin tantalum wire.

The radial acceleration of the surface of the wire will be measured by a VISAR \([4]\) and the motion of the surface will be modelled using a commercial computer code, LS-DYNA \([5]\). In this way the constitutive equations of the tantalum at high temperatures under shock conditions will be realised and the full scale target can be modelled.

The target needs to survive for an operational period of one year, corresponding to \(\sim10^8\) pulses. A shorter lifetime could be contemplated with more frequent target changes. The problem is of fatigue life. It will be possible to pulse the wire for long periods of time in the test and obtain real experimental evidence of the fatigue life. This is something that is unlikely to be practical with in-beam tests.

Finally, some in-beam testing is planned to confirm the VISAR measurements with the wire test and the resultant modelling.

2. PULSE CURRENT IN A WIRE

It is well known that high frequency currents flow on the surface of conductors \([6]\). The case of a voltage pulse applied across a conductor is slightly different. Solving Maxwell’s equations in this case yields a diffusion equation (cylindrical coordinates),

\[
\frac{\partial j}{\partial t} = \frac{1}{\mu_0\sigma} \left( \frac{\partial^2 j}{\partial r^2} + \frac{1}{r} \frac{\partial j}{\partial r} \right)
\]

where \(\sigma\) is the electrical conductivity and \(\mu_0\) the permeability of free space. An analytical solution can be found for several transient cases \([7,8]\).

For an electric field applied instantaneously at time, \(t = 0\), for an indeterminate time, to a long bar of radius \(a\), the solution is,

\[
J_z = j_{0z}\left[1 - 2 \sum_{n=1}^{\infty} e^{-\alpha_n r} J_0(\alpha_n a) J_1(\alpha_n a)\right]
\]

where \(\kappa = 1/\mu_0\sigma\), \(J_0\) and \(J_1\) are Bessel functions with roots \(\alpha_n\), and \(j_{0z}\) is the amplitude of the pulse current density. Figure 1 shows the relative power density, \(p/p_0\) dissipated in the wire as a result of ohmic heating as a function of the radius \(r\) within a tantalum wire at a temperature of 2000 K, at different times. It will be seen that it takes over 300 ns for the power at the centre of the wire to reach 80% of the peak value.
In addition to the thermal forces there are “pinch-forces” due to the magnetic field, \( B \), acting on the current \([6]\). The radial force per unit volume of the wire is \( jB \). The stresses (\(-50\) MPa) are comparable to, but generally less than, the calculated thermal stresses but so far have not been included in the modelling studies \([9]\).

3. CHARACTERISTIC TIMES

The characteristic time that the current takes to reach the centre of the wire is,

\[
\tau_i \approx \frac{a^2}{\kappa}
\]  \hspace{1cm} (3)

The thermal shock wave travels through the wire at the speed of sound in the metal \([10]\),

\[
S \approx \sqrt{\frac{E}{\rho}}
\]  \hspace{1cm} (4)

where \( E \) is the modulus of elasticity and \( \rho \) the density of the metal. To damage the material by thermal shock, sufficient energy must enter the material fast enough to create stresses that exceed the elastic limits. If the energy enters slowly little thermal stress will result. In general the energy should be delivered in a time that is less than the time, \( \tau_s \), taken for the shock wave to travel from the outer surface to the centre of the object,

\[
\tau_s = \frac{a}{S}
\]  \hspace{1cm} (5)

This means that if the target is “small” compared to the pulse length, \( \tau_0 \), then there will be little shock produced. Hence, for shock to occur it is necessary that,

\[
\tau_s \geq \tau_0 > \tau_j
\]  \hspace{1cm} (6)

To fulfill this condition the wire must be less than \(-0.25\) mm in radius.

3.1. Minimising the shock by adjusting the time structure of the proton pulses

The above suggests a way to minimise the shock on a solid target in the neutrino factory. The proton current pulses will be made up of a train of \(~1\) ns long micro-pulses. If the pulse length is long so that the micro-pulses are sufficiently far apart, the shock will be from individual micro-pulses and not from the combined effect of the macro-pulse. This has been confirmed by Skoro \([9]\) in his modelling studies with a target, 2 cm diameter, 20 cm long. With 10 micro-pulses the energy density in the target will be reduced from \(300\) to \(30\) Jcm\(^{-3}\), corresponding to only \(10\) K temperature rise for each micro-pulse.

4. THE PULSE POWER SUPPLY

The power supplies for the ISIS \([11]\) extraction kicker magnet produce a square wave pulse variable in amplitude up to \(8000\) A, \(700\) ns long with a rise time of \(100\) ns. The pulse forming network can be altered to produce a triangular pulse (no flat top) with the same rise time and amplitude, and a \(200\) ns fall time. This modified power supply will be used for the wire test.

REFERENCES

11. ISIS web site, http://www.isis.rl.ac.uk/