A HIGH POWER RADIATION COOLED TARGET FOR A NEUTRINO FACTORY

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Abstract

A solid target is being considered for the production of pions by intense high-energy proton beams for a neutrino factory. The target would consist of a rotating ring or a string of discrete bars travelling in a circle. The target would rotate in vacuum and the power would be radiated to the water-cooled walls of the vacuum chamber. Steady powers of up to 100 MW can be dissipated by thermal radiation at temperatures of ~2500 K, using a suitable refractory material such as tantalum or tungsten. Under thermal cycling and pulsed beam conditions, the thermal stresses and shock induced in the toroid are being studied. This is expected to significantly reduce the power capabilities and shorten the life by fatigue. The present design of the facility requires an average power dissipation in the target of up to 1 MW; this appears feasible at present. It is proposed to levitate, guide and rotate the target by electromagnetic forces generated by suitable arrangements of coils. A target wheel variation is also being considered for practical reasons.

1 INTRODUCTION

A toroid or band, rotating in vacuum and thermally radiating its power to water-cooled vacuum chamber walls could provide a simple, clean and reliable high power target for pion production in a neutrino factory [1]. It would not require beam windows between the incoming proton beam and the outgoing pion beam. A similar band target has been proposed by King [2] but is cooled by jets of water and rotates in atmosphere.

2 POWER DISSIPATION IN THE ROTATING TOROID

Figure 1 shows schematically a ring or toroid, of radius *R*, and circular cross-section, radius *r* (1 cm), rotating at velocity *V*, in a vacuum. The proton beam passes through a length *L* (20 cm) of the toroid at a small angle to its plane, dissipating energy *Q*, and heats the target to a temperature T_{max}. As the ring rotates it radiates heat to the surroundings at temperature T_e and enters the beam again at temperature T_0. The power dissipation and temperature of the toroid can be calculated by using the relation for the thermal capacity of the target and Stefan's Law of radiation [3].

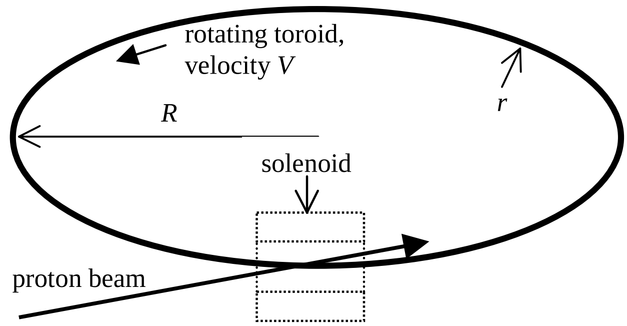

Figure 1: Schematic diagram of the rotating toroid.

To collect the pions produced in the target, a large solenoid [1], producing a central field of 20 T, encloses the interaction region. This is the reason that a band is used, as opposed to a wheel with spokes, so that it can thread the axis of the solenoid without cutting it.

Assuming a surface thermal emissivity $\varepsilon = 0.3$ and $r = 2$ cm, a power of 1 MW can be dissipated in a toroid of 20 m radius rotating at 1m/s [3]. At 10 MW power dissipation, the toroid could be 40 m radius and rotating at 20 m/s.

Improving the thermal emissivity will increase the power dissipation. A value of 0.8 can be achieved by effectively creating a rough surface; for example, by applying a suitable surface coating, the addition of fins or drilling small holes in the surface. A larger target section increases the area for thermal emission, but this could decrease the pion yield due to self-absorption and reduce the collection efficiency of the solenoid through enlarging the effective emittance of the pions.

3 PULSED EFFECTS

If the proton beam is pulsed, then some of the power dissipation relations are modified. Assume that the proton beam has a very short pulse length (~1 ns) and a repetition rate of *f* (Hz). When the toroid moves slowly, the volumes "illuminated" by consecutive pulses of the proton beam overlap and gradually separate as the toroid rotates faster or the repetition rate falls. The pulses are just separate when the speed and frequency are given by (this condition is assumed for the remainder of the paper),

$$V = L\,f \qquad (1)$$

For a target length of 20 cm and a repetition rate of 100 Hz, this speed is 20 m/s. At higher speeds the pulses are separate and the toroid is effectively larger than necessary. The parts of the toroid heated by the beam may cool more before they pass back into the beam, but the maximum temperature is still limited (by T_{max} ~2500 K for tantalum). Thus the peak power that can be dissipated is given by,

$$W = Q\frac{V}{L} = \pi r^2 \rho L S\left(T_{max} - T_e\right) f \qquad (2)$$

where ρ is the density of the target and S the specific heat. For a tantalum target, $W = 0.32\, f$ MW, which is 16 MW at a repetition rate of 50 Hz.

4 TEMPERATURE RISE, STRESS, SHOCK AND FATIGUE

The temperature of the toroid rises abruptly on entering the proton beam. The temperature change for uniform energy deposition is,

$$\Delta T = \frac{W}{\pi r^2 \rho S V} \qquad (3)$$

At 1 MW the temperature rise is 136 K with the toroid at a velocity of 10 m/s.

Large temperature rises are to be avoided because of the thermal stress and shock induced in the structure. The tantalum is weak at high temperatures. Figure 2 shows the temperature rise as a function of repetition rate (velocity), $f = V/L$. At 10 MW power dissipation, the velocity needs to be 50 m/s (f = 250 Hz) to keep the temperature rise down to 200 K. The stresses and high velocities are likely to limit the rotating toroid to ~10 MW.

As the toroid starts to radiate the power, a gradient is set up across the section radius, r. In fact the situation is more complicated than this since the beam, whether uniform or not, enters the toroid at an angle and produces additional longitudinal and radial temperature gradients.

The temperature gradients and the mechanical stresses, shock and fatigue are being estimated using a finite element method computer code, ANSYS. Since the energy is deposited in the target element in such a short time (~1 ns) the calculations show considerable shock effects even at temperature rises of 100-200 K. These calculations may show that the allowed power dissipation is restricted to quite low values – perhaps 1 MW.

However, calculations by King [2,4] of the stresses in a water-cooled cupronickel rotating band target indicate that the problem is not severe at the 1 MW level. Nickel has a larger specific heat than tantalum and hence will give smaller temperature rises. Also, the experience of the pulsed targets [5] at ISOLDE (CERN) and the p-bar target [6] at FNAL indicates that dissipation of 1-10 MW is possible at the power densities that are required. However, fatigue may limit the lifetime of the target at the relatively high repetition rate.

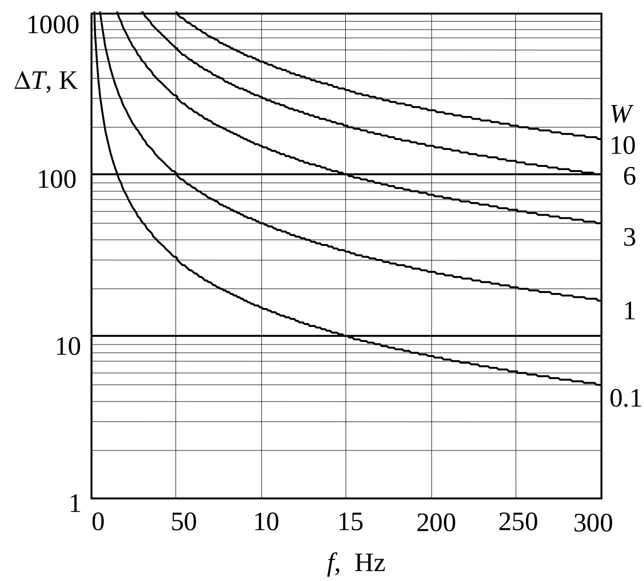

Figure 2: Temperature rise as a function of the repetition rate at different power dissipations, W (MW).

5 LEVITATION

Electromagnetic levitation and guidance of the toroid and rotation by linear motors results in no moving parts (except for the toroid) in the vacuum and no physical contact with the toroid.

Preliminary calculations of the ac magnetic fields required to levitate the toroid and to drive it round are found to be reasonable. The eddy current loses in the toroid are 50-100 kW. Detailed calculations and the field shaping required to provide stable operation have yet to be made.

6 INDUCED FIELDS IN THE SOLENOID

The rotation of the toroid through the 20 T solenoid produces eddy currents, which circulate about the axis of the target section. They produce a braking effect on the rotation of the toroid both on entering and exiting the magnetic field. The braking can be overcome by ~10 kW of additional drive. There is also a radial constricting pressure on the target section of ~15 bar. Neither effect would appear to be a major problem.

7 SOME PRACTICAL CONSIDERATIONS

The toroid has to be threaded through the high field solenoid. The toroid could be made in parts and then fastened together to make a rigid structure. However, this makes maintenance and repair difficult, particularly since the whole region will be very radioactive and require remote handling.

An alternative is to have discrete target bars, 20 cm long, which can be individually levitated and shot through the solenoid. This scheme has the advantage that a failure of any one target is not catastrophic as in the case of the toroid. Also, maintenance and replacement of individual targets is easier.

Extending this idea, it would be possible to have a large number of individual targets, which are shot through the solenoid and then stored for a given time to cool before being taken up again. This allows the equivalent of a very large radius toroid and time for the individual targets to cool to a lower temperature. Then, the maximum temperature of the targets could be reduced and materials with lower melting points and higher specific heats than tantalum or tungsten can be chosen. This will reduce the thermal shock and increase the target fatigue life. Figure 3 shows the system schematically.

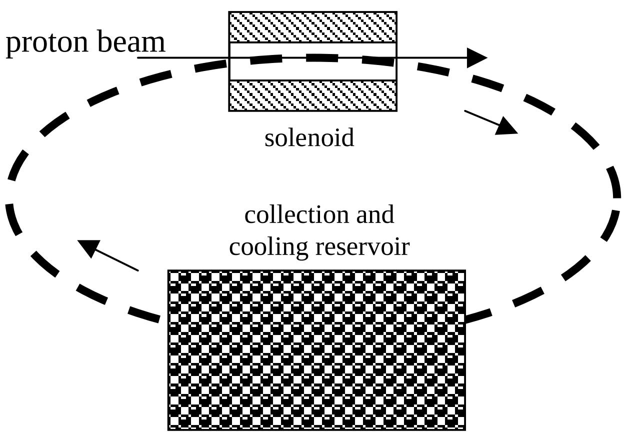

Figure 3: Levitated target bars are projected through the solenoid and guided to and from the holding reservoir where they are allowed to cool.

Cooling by thermal radiation is possible but it will take a long time at low temperatures. It takes ~4 minutes for a tantalum bar to cool from 1000 K to 800 K. Hence it may be necessary to use a flow of helium gas in the reservoir.

Another possibility is to construct a wheel consisting of spokes holding a target bar at their end. The assembly would rotate in a plane perpendicular to the beam. The solenoid would have to be split into two halves as in a Helmholtz coil. The target wheel could be virtually self-contained in its own vacuum box. This would greatly help in containing the radiation and contamination. The target could be removed as a unit for maintenance purposes and would also reduce the local radiation levels when other nearby items required access. Figure 4 shows the target wheel in the solenoid schematically.

Cooling would be by thermal radiation, as in the toroid. For 1 MW of power dissipated in the target, at T_{max} ~2500 K, with a 100 K temperature rise, the peripheral speed of the wheel would be 5.5 m/s and the diameter 11 m.

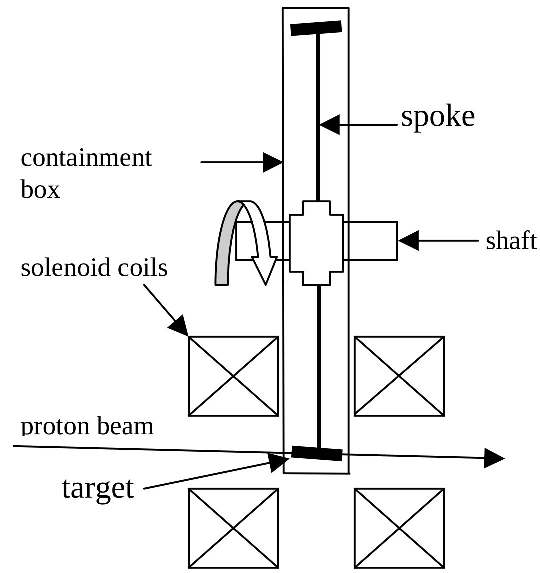

Figure 4: Schematic diagram of the rotating target wheel.

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