

THE SINUOUS TARGET

R. Zwaska, FNAL, Batavia, IL 60510, USA

Abstract

We report on the concept for a target material comprised of a multitude of interlaced wires of small dimension. This target material concept is primarily directed at high-power neutrino targets where the thermal shock is large due to small beam sizes and short durations; it also has applications to other high-power targets, particularly where the energy deposition is great or a high surface area is preferred. This approach ameliorates the problem of thermal shock by engineering a material with high strength on the micro-scale, but a very low modulus of elasticity on the meso-scale. The low modulus of elasticity is achieved by constructing the material of spring-like wire segments much smaller than the beam dimension. The intrinsic bends of the wires will allow them to absorb the strain of thermal shock with minimal stress. Furthermore, the interlaced nature of the wires provides containment of any segment that might become loose. We will discuss the progress on studies of analogue materials and fabrication techniques for sinuous target materials.

INTRODUCTION

We propose to generate a new, engineered material for use in high-power accelerator targets. This material will be composed of a multitude of interlaced wires, or rills, of small dimension. The rills will be made of a thermal-shock resistant material, but will not be subject to stress accumulation due to their small size. The intrinsic bends of the wires will allow them to absorb the strain of thermal shock with minimal stress. The solid bulk of this material will have a dramatically reduced modulus of elasticity than the bare material, greatly improving its resistance to thermal shock. Furthermore, the interlaced nature of the wires provides containment of any segment that might become loose.

This material could accommodate dramatically higher beam powers without breaking itself to pieces because it is strong on the micro-scale, but resilient and flexible on the meso-scale. The challenges will be fabricating this material and devising a cooling scheme.

BACKGROUND

A high-power target is an integral part of a neutrino beam, muon beam, and areas outside HEP such as neutron and rare isotope sources. The target rests in the center of the entire facility; it is within the target that the majority of the transformation occurs from an intense proton (or other species) beam produced by the accelerator, to a beam of unstable or rare particles suitable for experimentation. The target is a singular item, being small on the scale of other beam components. Yet, it bears the brunt of thermal, mechanical, and radiation effects [1].

Intense beam facilities operate targets at the edge of their capability [2]. Frequently, the intensity of a facility is limited by the target, or compromises are made in efficiency to make the target more survivable. Extending the capability of targets is central to building the next generations of all these facilities.

The key novelty of the sinuous approach is to engineer a material's properties to make it more survivable. We capitalize on a counter-intuitive fact: a stronger material is often inferior as a target material.

The actual factor we are interested in is the stiffness of the material which often goes hand-in-hand with strength. Particularly, we are concerned with a material's modulus of elasticity (or bulk or Young's modulus). This factor is crucial as it is what causes material to break under the influence of beam (short of melting). As a beam passes through the material, its energy deposition is thermalized producing a very rapid temperature rise correlated to the spatial intensity of the beam. The beam necessarily has a non-uniform profile, leading to uneven heating of the material. The material will attempt to expand at a local level in response to the heat, but cooler areas will resist this change. The difference in expansions must be equalized through the application of stress to compress or expand the material. That stress, S , is directly correlated to the length difference to be corrected (strain, ϵ) and the bulk modulus, K : $S = K \times \epsilon$. If this stress exceeds the yield strength of the material, it will start to fail. This is a predominant design requirement for targets and other significant mechanical components. Figures of merit have been designed using these and other parameters to evaluate the suitability of various target materials [3].

Unfortunately, for most materials strength is directly proportional to the bulk modulus: a strong material will be stiff. We desire a material with high intrinsic strength on the micro-scale, but very flexible: having a low bulk modulus. The most straightforward way to achieve this is to make the material into a spring. Then, to build a bulk, these springs can be overlaid and combined to build up a material that is nearly uniform on the meso-scale of the proton beam. The temperature-induced strain on this material will be negligible to its ability to expand, and strains will be non-existent.

There are further advantages of the small scale of the primary material. The cross-section will be so small that the heating will be uniform on the length scales of the material, so it will simply expand uniformly at the micro-scale. Stress waves will be inhibited as they also depend on non-uniform heating and propagation through a bulk: any waves would simply travel along the wires. The material can also be made more resistant to radiation damage effects as the lattice dislocations in a material attempt to migrate through the bulk until reaching a grain boundary, and further to the exterior of the material. As this material will be much smaller, the

lattice will be able to heal more quickly. The wire nature of material also leads to a very high ratio of surface area to volume, which could be advantageous for cooling or specialized processes where isotopes are extracted from the material. Finally, we can expect that if a small number of wire breaks occur that they will be inconsequential; broken wires will be constrained within the matrix of the bulk.

The sinuous nature of the material will necessarily lead to a loss of apparent density. For some applications this is consequential as the depth of focus of subsequent optics or beam ducts is limited. For example an ideal neutrino target would have a length of 10s of cm. Comparing to graphite, which has a density of 1.81 g/cc, Tungsten could be used (19.25 g/cc). A packing fraction of 10% would be adequate to regain density. Tungsten generally cannot be used as a bulk solid for neutrino targets, but may be suitable in sinuous form.



Figure 1: Example of a possible one-dimensional unit of which to build the bulk material. Individual spring-like elements can be interlaced and interconnected to construct a three-dimensional material. The individual elements will be resistant to the effects of thermal shock.

FABRICATION

The mechanical advantages of the sinuous material are nearly self-evident, but how to put the pieces of material into the correct arrangements needs to be established. Primarily, two general techniques will be investigated: additive manufacturing, and the knitting/weaving/braiding of wire stock.

The processes of turning wires into 2-dimensional interlaced materials are well-established. Many options exist including knitting, weaving, and braiding. Some 3D materials have also been produced, but are frequently simply joined 2D materials or slightly thickened versions. Those

approaches risk delamination in the presence of radiation as has been observed with some composite materials [1]. Some development may be required to retool a vendor to produce the material we need.

The nature of the sinuous material is different than a composite. A composite is often formed of many wires or fibers, but it is firmly encase in a matrix material that keeps the fibers together. The matrix also constricts its ability to deform and has substantial internal stresses. Our concept is like a composite without a matrix where we deliberately avoid any stress. However, we have to have an approach to keep the material whole without the matrix.

Additive manufacturing appears a very promising approach to producing these materials. Devices exist to produce objects made of refractory materials with feature sizes as small as 20 μm . Several techniques are available; the leading contender is Direct Laser Sintering or Fusion whereby a powder bed is sintered together with a laser. Layers of powder are added one-by-one. This has the advantage that the powder supports the above material so that complicated shapes can be formed. Another approach is electron beam direct manufacturing where an electron beam melts a stock piece of material onto a growing object. The electron beam approach typically has larger features and often does not have underlying support, but is more flexible.

Furthermore, there are existing materials which may act as intermediate analogues of our desired material. Flexible graphite, reticulated metal and ceramic foams, and other materials offer some of the flexible benefits of a sinuous material, but generally are still made of rigid strut-like members.

COOLING

Heat removal is vital to a target, particularly if light elements such as carbon and beryllium are replaced with a heavier one like tungsten or tantalum. Cooling can be achieved through conduction, transfer to a gas, or radiation. Conduction will be partially compromised by the sinuous approach, so the others must be investigated.

Radiative cooling is simple with tungsten which comprises the filaments of most incandescent light bulbs. The complication is that the optical path may be long from the interior to the exterior of the material. Furthermore, there would likely need to be a fluid (liquid or gas) at that point to carry the heat away from a compact target.

Direct gaseous cooling of the sinuous target would take advantage of the high surface area. The complication would be the relatively small pore size which would restrict flow. A relatively simple solution to this would be to manufacture cooling channels or capillaries into the material to allow greater flow. This approach would be simpler to implement with additive manufacturing than knitting.

CONCLUSION

We have proposed a new type of engineered material: the sinuous target. This material, if realized, has the potential

to extend the reach of solid targets with high-power beams (multiple MW). A research program will build and test several potential materials to evaluate the effectiveness of this approach, and establish the performance limits that might be expected.

ACKNOWLEDGMENTS

This work is supported in part by grants from the US Department of Energy under contract DE-FG02-12ER41800.

REFERENCES

- [1] P. Hurh *et al.*, “High-Power Targets: Experience and R&D For 2 MW”, Proc. PAC11, <http://accelconf.web.cern.ch/AccelConf/PAC2011/papers/weods2.pdf>
- [2] S. Cousineau, “High Power Proton Beam Facilities: Operational Experience, Lessons Learned, and the Future”, Proc. IPAC15.
- [3] A. Ahmad *et al.*, “Generic study on the design and operation of high power targets”, Phys. Rev. ST Accel. Beams, **17**, 024701, 2014, <http://link.aps.org/doi/10.1103/PhysRevSTAB.17.024701>.