Possible Target Options

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WATER COOLED SOLID TARGETS

- For high energy drivers, a desirable target material should have a medium to high Z. For low energy drivers the targe should be made from low Z material. The target material should be ductile, with high thermal conductivity and should be self annealing above 200 C. The coolant should not corrode the target. Copper and silver targets are obvious medium Z target materials. A less obvious candidate is a titanium or niobium-titanium alloy target. These materials are strong and non-corrosive. The problem with niobium-titanium is its poor thermal conductivity, but the material could be subdivided into fine wires or concentric thin wall pipes that carry the water. For low z targets carbon and aluminum are candidate materials.

- Cooling the target from the outside is limited by the cooling area, the heat transfer coefficient, and the heat conduction from the center of the target. The target could be subdivided and the coolant could be run through the target. Thus the coolant becomes part of the target. Pressurized water should be considered as a coolant. At a water mass flow of 1 kilogram per second about 400 kW can be removed for a 100 C temperature rise.

- A Gatling gun type of target with many parallel cooling paths is a possibility. A water-cooled Gatling gun type target will have a number of mechanical and seal problems.

RADIATION COOLED SOLID TARGETS

- Radiation cooled targets should be made from a high melting point material. Low Z targets will have much less proton energy deposited within them per pion produced, but low Z targets will require a more protons in the beam in order to generate the required number of pions. High Z targets produce more pions for a given proton intensity at 16 Gev, but the energy absorption per pion produced is higher for high Z materials. If one uses a low Z material for the target, such as carbon, the proton beam energy should be reduced. At 2 to 4 GeV, carbon will produce more pions per unit power into the target of any material. I believe that the yield per MW is higher for carbon than for high Z material at higher beam energies. There are two problems with 2 to 4 GeV beams. The first is the low energy driver current must be higher for a given beam power. The second is that pion production from targets hit by lower energy beams favors the production of positive pions. A low energy machine will produce about 60 percent more positive muons than negative muons. For a neutrino factory this may not be a problem. However, the low energy driver concept does not fit in with existing machines at either Fermilab or Brookhaven. For the available drivers, some models suggest that medium Z materials are best for the target.

Possible Elemental Candidate Materials for Targets

Element	Z	Density (g cm^{-3})	Melt T (C)	Boil T (C)	Remarks
Carbon	6	~1.8	3350	4827	low Z, radiation or water-cooling
Aluminum	13	2.70	660	2467	low Z, possible water-cooled
Titanium	22	4.54	1660	3287	moderate Z, ductile, non corrosive, Possible water-cooled candidate
Nickel	28	8.90	1453	2732	moderate Z, Magnetic, water-cooled?
Copper	29	8.96	1083	2567	moderate Z ductile, thermal conductive Possible water-cooled candidate
Gallium	31	6.09	29.8	2403	mod Z, Possible liquid cooling, corrosive
Niobium	41	8.57	2468	4742	medium Z, ductile, non-corrosive, Water-cooled or radiation cooled
Molybdenum	42	10.2	2617	4612	medium Z, possible radiation cooling
Silver	47	10.5	962	2212	medium Z, ductile, thermal conductive Possible water-cooled candidate
Indium	49	7.31	156.6	2080	medium Z, Possible liquid cooling
Tin	50	7.30	231.9	2270	medium Z, Possible liquid cooling
Tantalum	73	16.7	2996	5425	high Z, possible radiation cooling
Tungsten	74	19.3	3410	5660	high Z, possible radiation cooling
Rhenium	75	21.0	3180	5630	high Z, possible radiation cooling
Osmium	76	22.6	3045	5030	high Z, possible radiation cooling
Mercury	80	13.5	-38.9	357	high Z, Possible liquid cooling, poisonous
Lead	82	11.4	327	1740	high Z, Possible liquid cooling
Bismuth	83	9.7	271	1560	high Z, Possible liquid cooling

Low Z materials have less of the beam energy deposited in the target for a given radiation length. Low Z targets have maximum pion production at lower proton energies (2 to 4 GeV). The ratio of positive pions to negative pions is higher for low Z targets hit with protons at optimum energy. The energy deposition per unit volume is lowest with low Z low density targets.

High Z materials have more of the beam energy deposited in the target for a given radiation length. High Z targets have maximum pion production at higher proton energies (8 to 16 GeV). The ratio of positive pions to negative pions is lower for a high z target hit with protons at optimum energy. The energy deposition per unit volume is highest for high z high-density targets.

- Candidate materials for radiation cooled target include carbon (a low Z material) niobium, molybdenum, (medium Z materials) tantalum, tungsten and rhenium (high Z materials). It is useful to look at the 1 atmosphere boiling temperature for the candidate radiation cooled materials. Low vapor pressure at the operating point is needed. High melting point refractory materials are not very ductile, they are poor conductors of heat, and they do not tend to be self-annealing at moderate temperature. The reaction of the target to the shock loads introduced by intense proton beams has been a problem. Many of these materials will break due to shock waves under an intense proton beams. A composite target with a refractory metal shell and a liquid copper or aluminum center may be an option worth investigating.

- Radiation cooled targets can be put into a rotating Gatling gun type of target. A radiation cooled Gatling gun target could be attractive if the shock wave problem can be solved. A Gatling gun type of target may require more radial space. A larger, lower field, capture solenoid may be needed.

LIQUID METAL TARGETS

- Liquid targets should solidify at room temperature. The liquids should be non-corrosive and should not dissolve or amalgamate with other materials. The radioactive daughters that result from the collision with protons should be considered. Medium to high Z liquids are desirable for high-energy drivers. Mercury, gallium, and bismuth can be eliminated for the above reasons. Lead, tin, and indium are possible liquid target materials. Indium-tin alloys will melt at near room temperature. Liquid metal targets in a pipe have been demonstrated. The shock waves formed in the liquid can rupture the can at high beam intensities into the target.

- The formation of liquid metal jets has been demonstrated. The liquid metal jets will fly apart due to the shock caused by the intense proton beam. The pions are formed before the target explodes. The jet fragments into pieces with a tangential velocity approaching 100 meters per second (225 MPH). Do we want particles flying in the magnet bore at that velocity? I would expect the exploding jet would cause erosion of the magnet bore. A liquid metal jet target may be a problem in a magnetic field. The magnetic field can break up the flow stream unless it is along the axis of the solenoid. The high magnetic field may reduce the rate of fall for the target liquid; a liquid fog may be formed. A liquid jet target might be a good solution if there were no magnetic field at the target. The explosion of the jet that has been hit by the beam may cause serious problems. I do not believe that liquid jet target are very attractive because the target will go everywhere.

- Mercury targets have the additional problem of mercury being toxic. In addition mercury amalgamates with most metals that would provide good heat transfer from the mercury to the fluid taking the heat away. The only common metal not dissolved by mercury is iron. Perhaps some of the stainless steels and nickel alloys can withstand mercury, but they may be magnetic.

A POSSIBLE TARGET SOLUTION

Radiation cooled targets appear to have many advantages. For low Z materials, carbon is the only choice. The temperature of a carbon target is limited by sublimation from the target. Carbon target may be OK up to temperatures of 2100 C. At the 1 MW beam level, a single carbon target appears to be possible. Above 1 MW, the Gatling gun target might be better. At medium Z targets made from niobium appear to be the best choice. The upper temperature limit is about 2000 C. For the high Z targets Tantalum, Tungsten or Rhenium appear to be the best choices. The upper temperature limits for these targets are from 2500 to 2600 C. Medium Z radiation cooled targets will probably have to be gatling gun targets even at the level of 1 MW beam energies. It is unlikely that any of the high Z radiation cooled targets will work at 1 MW beam power. Because of the high Z and high density, the high Z targets will be thinner and shorter. Over one order of magnitude more power must be removed per unit area for the high Z targets. Targets made of high Z materials alone are not attractive.

In a view graph at Orcus Island, I presented the heat that can be transferred per unit area (W m^{-2}) as a function of target temperature (K). The results for ε = 1 are given below:

1500 K (1227 C)	0.29×10^6
1750 K (1477 C)	0.53×10^6
2000 K (1727 C)	0.91×10^6
2250 K (1977 C)	1.45×10^6
2500 K (2227 C)	2.22×10^6
2750 K (2427 C)	3.25×10^6
3000 K (2727 C)	4.61×10^6
3250 K (2977 C)	6.34×10^6
3500 K (3227 C)	8.53×10^6

For a 1 MW beam and the following target materials the estimated target temperature T is:

Material	L (m)	D (m)	Area (m^2)	Power (kW)	T (K)	Remarks
C	0.6	0.09	0.169	40	~1500	a single target OK
Nb	0.33	0.049	0.051	100	~2450	a 6 barrel Gatling gun OK
Mo	0.30	0.045	0.042	100	~2570	a 6 barrel Gatling gun OK
Ta	0.16	0.022	0.0090	200	>4500	Gatling gun not even OK
W	0.13	0.018	0,0074	200	>4700	Gatling gun not even OK
Re	0.12	0.017	0.0064	200	>4850	Gatling gun not even OK

Gatling gun targets may permit niobium or Molybdenum to be used as a target material. Because of their small volume high Z Gatling gun targets are ruled out. Gatling gun targets are potentially attractive except for the following. The radiation heat transfer form factor will not be 1.0 for a Gatling gun target. As result, the target will run hotter for a given number of barrels and a given beam power. Unless the Gatling gun target can be spun in the capture solenoid, the target will have to be behind the capture solenoid. Particles will be lost. Particles produced by one of the target barrels will be captured by another target barrel if the target is entirely inside the capture solenoid. It does not matter where the Gatling gun is some particles will be lost. The Gatling gun target will be attractive compared to a single carbon target only if the pion yield from the target is higher.

A single carbon target will work in the capture solenoid at the 1 MW level. The Gatling gun targets made from niobium may or may be more efficient. A study should be made on the effects of Gatling gun target placement on particle loss and re-absorption of pions into the Gatling gun target.

Another version of the Gatling gun target is the band saw target. A band saw target fabricated with niobium could be radiation cooled in a vacuum. The band saw approach allows one to increase the target radiating area without reducing the yield from the target. The yield from a band saw target will be lower than from a cylindrical target made from the same material, but its yield should be higher than for a gatling gun target inside the capture solenoid. A radiation cooled band saw target is worth considering if niobium or Molybdenum is suitable from an induced radiation standpoint. I do not think that high Z materials are suitable for even for the band saw target concept. As with all of the band saw targets that have been proposed, getting the band into and out of the capture solenoid is the problem. Changing bands in a high radiation environment will be a challenge, but in some ways the problem is similar to a self-threading projector for film.

Radiation cooled targets are attractive for their simplicity. If the target is a single cylinder, carbon is the only option for a radiation-cooled target. Perhaps one should seriously consider using a high-current low-energy (2 to 4 GeV) driver instead of a lower current 8 to 20 GeV driver. The low-energy driver will increase the pion production per MW of beam power. A carbon target is well suited to a lower energy beam. The low energy driver should be studied to see if neutron production is a problem and to see what other problems may occur besides the obvious one of having large beam currents in a low energy machine.

As to the liquid jet target, we should look at all of the problems they may cause. We should consider the effects of contamination of the whole machine with the liquid jet material. Is coating the wall of the vacuum chamber 200 meters down stream with the liquid jet material a good idea? I think not, when the jet is mercury. Is residual liquid from the jet going to make the neutron problem better or worse? Is the liquid jet going to contribute in a negative way to the control of radiation in the machine? The liquid jet target is rife with E H and S issues. Liquid cooled targets are different and should also be considered.