A Rotating Metal Band Target for Pion Production at Neutrino Factories and Muon Colliders*

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Abstract

A conceptual design is presented for a high power pion production target for neutrino factories and muon colliders that is based on a rotating metal band of either inconel alloy 718, titanium alloy 6Al-4V grade 5 or nickel. The band is 5 meters in diameter and is tangentially intercepted by a pulsed proton beam inside a 20 Tesla tapered solenoidal magnetic pion capture channel. The mechanical layout and cooling setup of the target are summarized and results are presented from realistic MARS and ANSYS computer simulations of pion yields, energy depositions and shock heating stresses. The target scenario is predicted to perform satisfactorily and with conservative safety margins for multi-megawatt pulsed proton beams.

1 INTRODUCTION

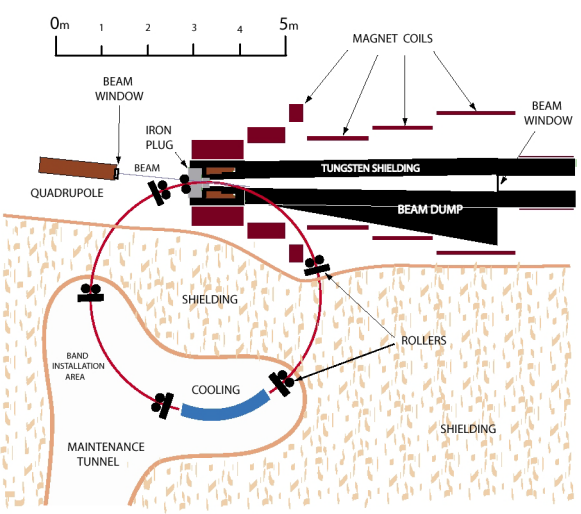

Figure 1: A conceptual illustration of the targetry setup.

This paper presents a target option for pion production at neutrino factories and muon colliders that is based around a rotating band geometry [1, 2, 3, 4, 5, 6]. It summarizes the material in reference [6].

2 MECHANICAL DESIGN SCENARIO

A plan view of the band target design scenario is shown in Fig. 1. A 2.5 meter radius circular target band threads through a solenoidal magnetic capture channel [7, 8, 4] to tangentially intercept the proton beam.

Three metals with track records as production targets or beam windows are considered as candidates for the target band: inconel 718 (a niobium-modified nickel-chromium-iron "superalloy"), titanium alloy 6Al-4V grade 5 and pure nickel.

The cross sectional dimensions of the band and its orientation relative to the proton beam for each of the 3 candidate materials are shown in Fig. 2, and the proton beam dimensions and the specifications and material properties of the band are enumerated in Table 1.

The band is in an air environment and is guided and driven by several sets of rollers at rotation speeds of order 1 m/s. Faster rotation minimizes heating pile-up from successive proton pulses but increases the eddy current drag in the 20 Tesla solenoid. A procedure has been developed [5, 6] for its routine installation and extraction.

Typically, approximately 7% of the proton beam energy is deposited in the band target as heat. The heated portion of the band rotates through a 2 meter long water cooling tank, as shown in Fig. 3. The flow rate and heat transfer parameters are relatively comfortable [6] even for few-MW proton beams – a flow rate of a few liters per second and heat transfer of some tens of $\mathrm{W/cm^2}$ – so forced convection is not required.

3 SIMULATIONS OF YIELD, ENERGY DEPOSITION AND STRESS

Probably the most critical issue faced in solid-target design scenarios for pion production at neutrino factories or muon colliders is the survivability and long-term structural integrity of solid targets in the face of repeated shock heating. A critical design parameter for assessing the shock stresses on the band is the energy contained in each bunch of the pulsed proton beam. The bunch repetition rate is less important because the beam-induced shock waves die down quickly enough for the bunches to be relatively independent in any reasonable muon collider bunch scenario.

Full MARS [11] tracking and showering Monte Carlo simulations of pion yields and energy deposition densities were conducted for incident proton bunches at representative 6 GeV and 24 GeV beam energies. Three-dimensional energy deposition maps from the MARS simulations were then used as input to finite element stress simulations using the commercial code ANSYS.

Fig. 4 shows the ANSYS predictions for von Mises stress development in the bands and Table 1 summarizes

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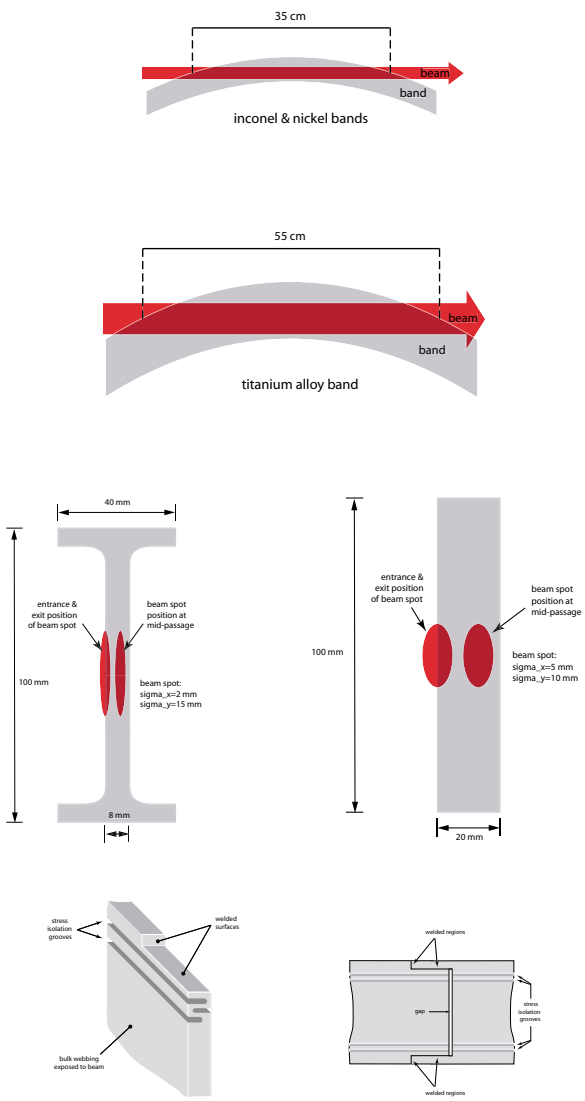

Figure 2: Several views of the target bands and position of the proton beam: plan views for the inconel or nickel bands (top) and for titanium (2nd row), with a vertical:horizontal aspect ratio of approximately 5.4:1; cross-sectional views for inconel or nickel bands (left, 3rd row) and for the titanium alloy band option (right, 3rd row); and three-dimensional (bottom left) and side (bottom right) views showing how the welds between band segments are mechanically isolated from beam-induced shock waves.

the yield, energy deposition and stress predictions from the MARS and ANSYS simulations. These have been benchmarked to muon colliders with the largest proton bunch charge normally considered [7] at collision: 4×10^{12} muons per bunch, which implies [7, 6] initially capturing a total of approximately 3.2×10^{13} pions and muons. where both signs have been summed. The beam-induced shock stresses at neutrino factories are typically less demanding [4, 5].

It is seen from the predicted stresses as fractions of the fatigue strength that the viability of inconel bands becomes

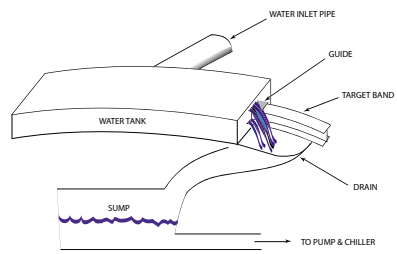

Figure 3: A conceptual illustration of the target cooling setup.

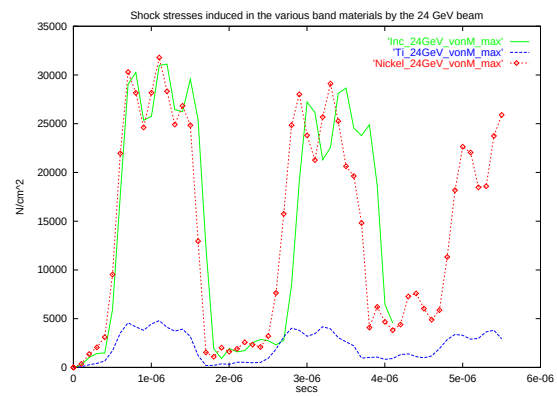

Figure 4: Predicted time dependence of maximum von Mises stresses on inconel 718, titanium alloy and nickel bands due an instantaneous energy deposition from a bunch of 1.5×10^{14} 6 GeV protons with transverse dimensions as given in Table 1.

borderline (53-69%) for the most stringent muon collider production assumptions but the titanium alloy should still provide a very conservative safety margin (10-14%), albeit with a pion yield about 20% lower than the other two candidate materials. Since successfully operating nickel targets [12] seem to evade predictions for low yield strengths, the suitability of nickel bands is not well predicted by these simulations and would need to instead be determined in test beam experiments.

4 CONCLUSIONS

In summary, the rotating metal band target concept appears to be a promising option for pion production targets at neutrino factories and muon colliders. The engineering aspects look manageable and initial simulations of pion yields and target stresses are encouraging for each of three candidate target band materials: inconel 718, titanium alloy 6Al-4V grade 5 and nickel.

5 REFERENCES

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Table 1: Specifications of the target band and assumed proton beam parameters, a tabulation of some relevant properties of the candidate band materials, and a summary of MARS and ANSYS predictions for pion yields, energy depositions and stresses. Units are indicated in square brackets. See text for definitions and details.

Property	**inconel 718**		**Ti-alloy**		**nickel**	
target band radius, [m]	2.5		2.5		2.5	
band thickness, [mm]	8		20		8	
band webbing height, [mm]	100		100		100	
full width of band flanges, [mm]	40		–		40	
beam path length in band, [cm]	35		55		35	
proton interaction lengths (λ)	2.1		2.0		2.3	
weight of band, [kg]	169		139		183	
horizontal beam-channel angle (α), [mrad]	100		100		100	
rms beam spot size at target (horizontal), [mm]	2		5		2	
rms beam spot size at target (vertical), [mm]	15		10		15	
average atomic number, Z	27.9		21.5		28.0	
average atomic weight, A	59.6		46.8		58.7	
density (ρ), [$\mathrm{g.cm^{-3}}$]	8.19		4.43		8.88	
interaction length (λ), [cm]	16.6		28.2		15.2	
radiation length ($\mathrm{X_0}$), [cm]	1.55		3.56		1.48	
melting point, [^{o}C]	1298		1660		1450	
heat capacity, [$\mathrm{J.K^{-1}.g^{-1}}$]	0.435		0.526		0.46	
thermal conductivity, [$\mathrm{W.m^{-1}K^{-1}}$]	11.4		6.7		61	
electrical conductivity, [$\mathrm{MS.m^{-1}}$]	0.8		0.56		14	
thermal expansion coefficient (α), [$10^{-5}/\mathrm{K}$]	1.3		0.88		1.31	
elastic modulus (E), [$10^{11}\ \mathrm{N/m^2}$]	2.3		1.1		2.1	
0.2% yield strength, [MPa]	1100 [10]		~ 960 [10, 13]		59 [10]	
fatigue strength [MPa], no. cycles	480-620 at 10^8 [9]		510-700 at 10^7 [10, 13]		N.A.	
proton energy [GeV]	**6**	**24**	**6**	**24**	**6**	**24**
captured π^+ yield/proton	0.102	0.303	0.080	0.249	0.102	0.105
captured π^- yield/proton	0.105	0.273	0.083	0.224	0.302	0.292
protons per pulse, $ppp^{3.2}$ [10^{13}]	15.5	5.56	19.6	6.78	15.5	5.39
proton pulse energy, $E^{3.2}_{pulse}$ [kJ]	149	214	188	260	149	207
max. energy density, $U^{3.2}_{max}$ [J/g]	32.0	31.7	25.6	21.3	32.5	37.4
max. temp. rise, $\Delta T^{3.2}_{max}$ [^{o}C]	74	73	49	40	71	81
max. von Mises stress, $VM^{3.2}_{max}$ [MPa]	330	360	72	68	330	340
% of fatigue strength	53-69%	58-75%	10-14%	10-13%	N.A.	N.A.

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