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in the Muon Collider/Neutrino Factory Project**

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# MOVING SOLID METALLIC TARGETS FOR PION PRODUCTION IN THE MUON COLLIDER / NEUTRINO FACTORY PROJECT

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## Abstract

The production of large fluxes of pions and muons using high-energy, high-intensity proton pulses impinging on solid or liquid targets presents unique problems which have not yet been entirely solved. We investigate the possibilities of using solid targets by choosing a metal of either extremely low thermal expansion coefficient or exceptionally high mechanical strength. Candidates are respectively Super-Invar and Vascomax 350 or Inconel 718. Moving targets in the form of chains or cables would be required for cooling purposes. These materials seem easily capable of surviving the beam pulses required for the largest beam power contemplated. Questions regarding radiation damage effects are being investigated.

## INTRODUCTION

The new frontier of multi-megawatt accelerators offers important new physics opportunities as well as interesting technical challenges. In particular, the production of large fluxes of pions and muons using high-energy, high-intensity proton pulses impinging on solid or liquid targets [1,2] presents unique problems which have not yet been entirely solved. The large required power and power density deposited in the material as well as the short pulse duration produce large, almost instantaneous local heating, and the resulting sudden thermal expansion can result in damage-causing stresses in solids and in the violent disruption of liquid jets. We concentrate on solutions based on solid metallic targets which, through their motion, carry the deposited power from the interaction region to a cooling bath.

The conditions created by the short beam pulses (rms width ~50 ns during recent experiments [3] and <5 ns for a final system [1,2] are very unusual. Intense, almost instantaneous, beam heating causes a fraction of the target volume to suddenly be in a highly compressed, inertially confined state. Subsequently this volume expands initiating strong vibrations in the material. The amplitude of these oscillations is such that large negative pressures (tensile stresses) or shear stresses can be generated exceeding the strength of the material and thus causing mechanical failure.

For a preliminary screening of possible materials, we assume that tensile and shear stresses will arise in the oscillations which are similar in magnitude to the initial compression. In fact, the natural tendency in most cases will be for the energy initially concentrated in a fraction of the target volume to rapidly spread over the entire

volume thus reducing subsequent peak values. However, vibration focusing effects can lead to unexpected stress concentrations. Computer modeling will be required once a candidate material is selected, and target geometries can then, if necessary, be modified.

## CANDIDATE MATERIALS

Two possible approaches to avoid stress induced failures are to either select extremely strong materials that may withstand the large stresses, or materials with extremely low coefficient of thermal expansion for which the thermal shock stresses will be minimized. In the present study we consider the alloys Vasco Max C-350 and Inconel 718 in the first category and Super-Invar in the second one. For comparison, we also include data for pure iron. Table 1 lists the thermal and mechanical properties of these materials.

For all these materials and for target radii ranging down to a few mm, the radial sound transit times are orders of magnitude larger than the energy deposition times of nanoseconds or even tens of nanoseconds. Heat diffusion times are longer still by several orders of magnitude. The initial compression is therefore inertially confined to good approximation and the subsequent oscillations are nearly adiabatic.

## STRESS ESTIMATES

To determine the initial compression we must first find maximum values of the energy density deposited by the beam. This was done by using the MARS code [4] for a number of different target radii, and by assuming a proton beam rms radius,  $\sigma$ , 2.5 times smaller than the target radius in each case. An example of such a calculation for iron is shown in Fig. 1 for a target radius of 7.5 mm, a beam rms radius of 3 mm and a 24 GeV proton pulse of  $16 \times 10^{12}$  protons. Table 2 lists maximum energy density values for a range of radii. Once the maximum value  $\epsilon_{\max}$  of the energy density (per unit mass) is found from these calculations for each case, we calculate the corresponding maximum compression  $P_{\max}$  for each material:

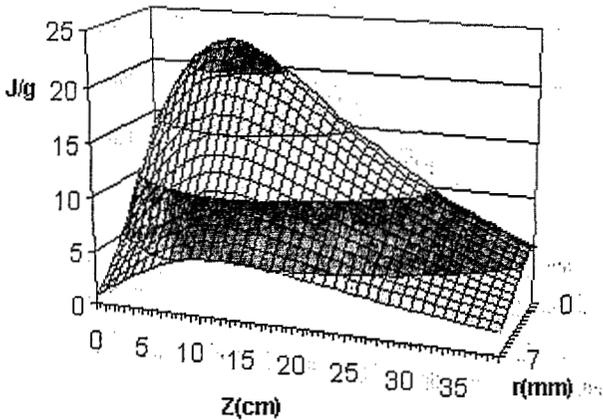
$$P_{\max} = 3 \times \epsilon_{\max} \times B \times \alpha / c_v$$

where  $B$  is the bulk modulus,  $\alpha$  the linear expansion coefficient, and  $c_v$  the specific heat at constant volume. The factor 3 is, for an isotropic material, the ratio between volumetric and linear relative expansions. These stress values are then appropriately scaled for the 1 MW and the 4 MW options of the Muon Collider/ Neutrino Factory project [1,2] the first of which calls for 15 pulse per second with  $17.3 \times 10^{12}$  protons per pulse, with both these numbers doubled for the second one.

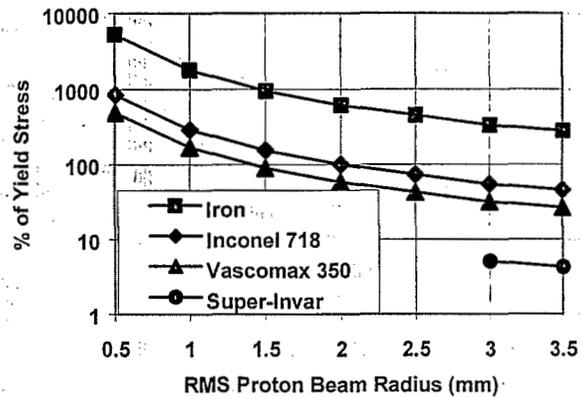
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**Table 1. Mechanical and thermal characteristics:**

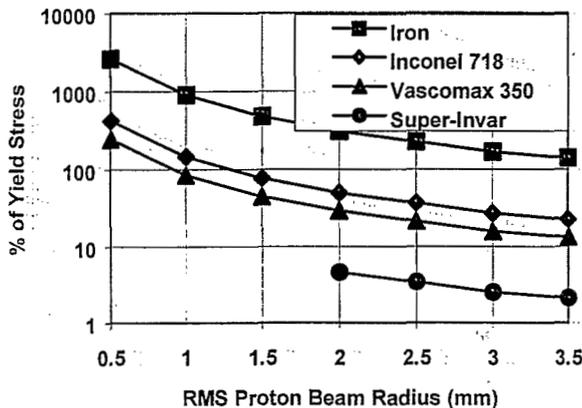
	Density	Linear Exp. Coeff.	Young Modulus	Bulk Modulus	Poisson Ratio	Specific Heat @ constant pressure	Thermal Conductivity	Yield Strength	Fatigue Endurance Limit
Symbol	$\rho$	$\alpha$	Y	B	$\mu$	$C_p$	$\lambda$	$\sigma_{0.2}$	$\sigma_{-1}$
Unit	$g/cm^3$	$10^{-6}/^{\circ}K$	G Pa	G Pa		J/(g $^{\circ}K$ )	W/(m $^{\circ}K$ )	M Pa	M Pa
Iron	7.87	12.5	205	171	0.30	0.478	80	170	~85
Inconel 718	8.19	13.1	200	158	0.29	0.435	11.2	1034	586
VascoMax C-350	8.08	15.0	200	167	0.30	0.450	25.2	2242	758
Süper Invar	8.15	0.63	144	88.9	0.23	0.515	10.5	276	~138



**Fig. 1** Three-dimensional view of energy deposition MARS values for a 3 mm rms radius 24 GeV,  $16 \times 10^{12}$  proton beam pulse on a 7.5 mm radius iron target.



**Fig. 3** Maximum initial stress as % of yield stress for the 24 GeV,  $34.7 \times 10^{12}$  proton beam pulses required for the 4 MW option.



**Fig. 2** Maximum initial stress as % of yield stress for the 24 GeV,  $17.3 \times 10^{12}$  proton beam pulses required for the 1 MW option.

In Figs. 2 and 3, we apply our criterion to both options of the Muon Collider/Neutrino Factory proposal [1, 2] by plotting these maximum stresses as percentages of the respective yield stresses for the different materials and for

a range of rms beam radii, with target radii 2.5 times larger. We see, for example, that for Vascomax 350 our criterion wouldn't be exceeded even for the 4 MW option down to a ~4 mm radius target which is smaller than envisaged. Super-Invar, while being further from reaching the yield stress is limited to larger radii due to the fact that its low expansion coefficient characteristic disappears at temperatures higher than ~120 °C. Also, results from radiation damage studies, reported elsewhere in these proceedings [5], indicate that Super-Invar may not be an appropriate choice.

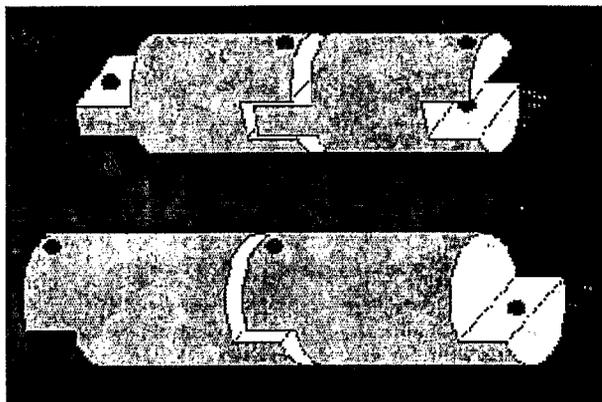
A somewhat more stringent criterion for estimating the resiliency of these materials is to compare the maximum initial stresses to the fatigue limit instead of the yield stress. In that case the results for Vascomax 350 and for Inconel 718 become similar, and indicate that target radii equal or larger than 4.5 mm and than 7.5 mm would be viable for the 1 MW and the 4 MW option respectively. Using fatigue limits is probably overly conservative since these limits, which are specified at low repetition rates, are known to increase substantially with frequency. We also see that iron or other alloys much weaker than the ones considered here would be inadequate even for the 1 MW option using either criterion.

**Table 2. Maximum energy densities deposited by  $16 \times 10^{12}$  24 GeV proton beam pulses in iron targets. Values for the other materials considered here will be nearly identical.**

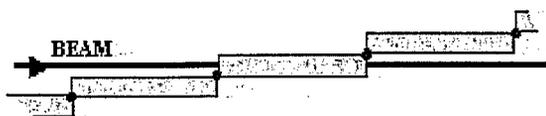
Proton beam rms radius [mm]	.5	1	1.5	2	2.5	3	3.5
Target radius [mm]	1.25	2.5	3.75	5	6.25	7.5	8.75
Maximum energy density [J/g]	305	105	55.6	36.0	26.5	22.1	16.5

**POSSIBLE IMPLEMENTATIONS**

Finally we show some schematic representations of possible chain configurations for moving targets as alternatives to the previously proposed "Band Saw" system [6] or the use of a metallic cable [7].



**Fig. 4** Examples of metallic chain links configurations showing rather compact designs with large metal to gap volume ratios.



**Fig. 5** Schematic of a chain with long links which, if surrounding hardware such as magnet coils permit, would allow each beam pulse to be coaxial with the target.

Cooling requirements dictate in each case the minimum velocity as well as the length for a chain of a given material and a given geometry. An estimated required velocity for a Vascomax C-350 chain for the 4 MW option would, for example, be 3 m/s and the total length would be ~35 m to transfer the power deposited by the beam to a 20 °C cooling bath without exceeding an internal target temperature of 300 °C and thus largely preserving the strength of the material.

**DISCUSSION AND CONCLUSIONS**

We conclude that solid moving metallic targets with very large tensile strength are viable candidates for a 1 MW and even a 4 MW Muon Collider/Neutrino Factory system and should therefore also be considered for other multi megawatt high energy proposals. It was also shown that more conventional solids such as iron can not be expected to work.

The choice between Vascomax C350 and Inconel 718 (or perhaps Inconel 750) may be influenced by the fact that Inconel isn't ferromagnetic and will therefore not be subjected to the rather large forces Vascomax chains will experience when entering and exiting a high solenoidal field. A disadvantage of Inconel is its low thermal conductivity which makes cooling slower and will thus require longer chains. It may be possible to improve this situation by providing cooling channels through the chain links.

The present stress and temperature estimates are thought to be conservative since no credit was taken for the advantageous frequency dependence of fatigue tolerance, nor for the possibility of using non-Gaussian beam profiles to reduce the peak energy density if necessary. Uncertainties about the survival of high-temperature stationary carbon targets and about the possibility of rapidly clearing large quantities of dispersed mercury for liquid jet targets [8] makes these moving solid targets a safer choice.

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