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R&D works on high-power targetry for neutrino factories

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Abstract

High power targetry is one of the major technical challenges to realize neutrino factories based on muon storage rings. Various R&D works have been carried out in the framework of international collaboration. Recent progress in a free mercury jet, material studies, and capture/focusing devices are discussed. Future prospects for R&D are briefly described.

1. Introduction

A neutrino factory based on a muon storage ring is a facility which produces intense neutrino beam. Fig. 1 shows a schematic of a possible neutrino factory complex. Pions are produced in the collision of an intense proton beam with a production target. Decayed muons from the pions are then phase-rotated and cooled so that they can fit into acceptance of the accelerator. The muon beam is accelerated up to 10–50 GeV and accumulated in the storage ring. At the long straight sections, the muons are decayed to emit the intense neutrino beam. The resultant beam has very small divergence such that it can travel a few thousand km. Precise knowledge of the neutrino beam and very low level of the background are strong merits of the muon-based system, as compared to 'conventional neutrino beam' based on pion-decay system.

Such beam would be used as an ultimate tool to study neutrino oscillation physics, especially to investigate CP violation in lepton sector. It could also be used for other neutrino physics and short-baseline experiments. It should be noted that intense cooled muon source, which inevitably obtained at early stage, would be used to study fundamental physics such as lepton flavor violation as well as various other fields such as material science, life science, and etc. It is also the fist step of a $\mu^+\mu^-$ collider.

Design studies have been carried out in US [1], EU [2], and Japan [3], showing that a neutrino factory could be built by using present accelerator technologies. To realize such a machine, R&D works have been extensively made on various fields, e.g., proton drivers, pion production and collection, muon cooling, and muon beam acceleration. Among them, targetry for pion production is one of the major technical challenge. In this paper, the targetry related R&D works are overviewed in connection with material studies.

2. High power targetry for neutrino factories

Development of targets which survive in the high power proton source is one of the main issues for future accelerator-based projects, such as neutrino factories, spallation neutron sources, and so on. Technical challenges are as follows:

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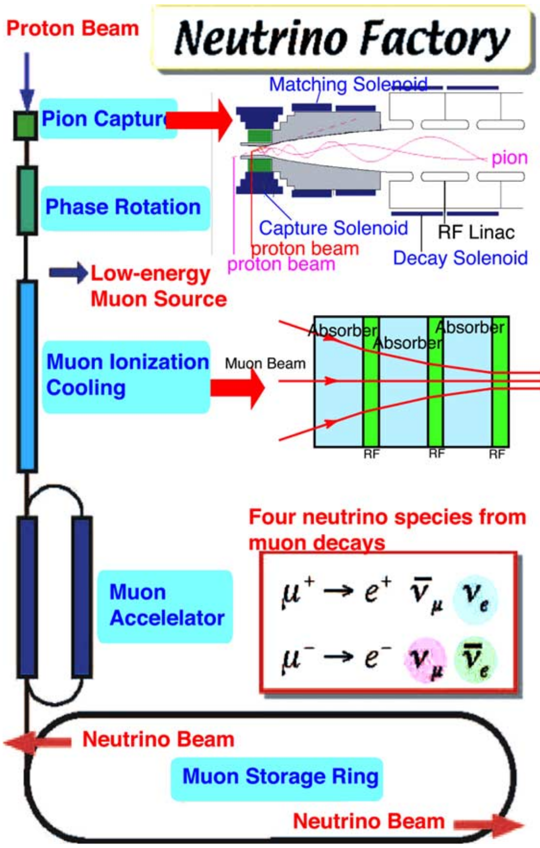

Fig. 1. Scheme of a neutrino factory.

- Removal of the heat deposited by a high power proton beam to avoid melting or vaporizing.
- Survival against thermal pressure waves in the pulsed beam.
- Long term stability against radiation damage.

In case of neutrino factories, to increase pion yield with relevant energy (0.1–0.3 GeV/c) and reduce initial emittance of the beam, the following factors should be took into account:

- High Z material is favored for high energy primary proton beam contrary to 'conventional' beam (Fig. 2). It is noted that for conventional beam low Z material is preferable to produce pions with energy of a few GeV.
- Small spot size (∼1 mm) and short-pulsed (∼ a few ns) of the beam is required.
- Magnetic devices, e.g. solenoids or magnetic horns, which capture/focus pions should be used in extremely high radiation environments.

Following three types of target are now considered as possible options:

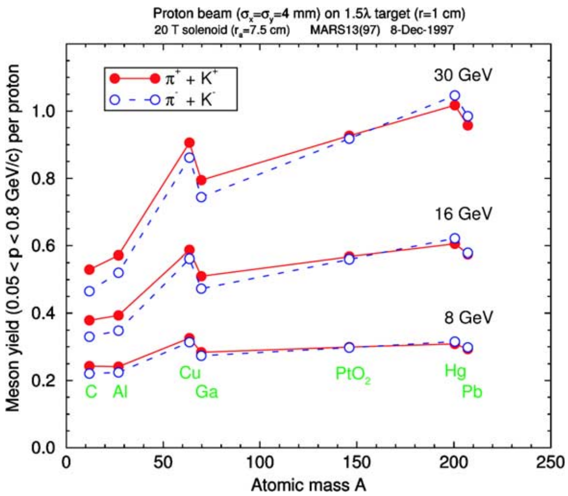

Fig. 2. Pion yield vs atomic number of target materials.

(i) stationary target,
(ii) moving target,
(iii) liquid metal target.

All target systems could be compatible with beam power of less than 1 MW. With higher power, however, first two might be problematic in view of thermal shock, which could break targets with only single shot pulse. Liquid metal targets are potential candidates which survive at 4 MW beam power. Confined liquid metal system, however, still need solid metal walls and/or containers, which could fail due to erosion or pitting associated with cavitation. A free mercury jet is preferable and considered as a base-line option.

In the following sections, R&D works on three subjects, i.e., a mercury jet target, material studies and collectors, are reviewed.

2.1. Mercury jet target

Fig. 3 shows a schematic view of a possible mercury jet target station in the 4 MW beam [1]. A mercury jet crosses a proton beam at an angle of ∼40 mrad. Both the jet axis and the beam axis are tilted to the magnetic axis so as to increase soft pion and to use a pool of mercury as a beam absorber/dump. Magnetic field at the interaction region is 20 T and decreases to 1 T over a few meters. Key issues on a mercury jet target are as follows:

- What is the dispersal of jet by interaction of proton beam? Do the droplets damage the target containment or nozzle?
- What is the effect of the magnetic field? Does it damp the effect of the beam-induced pressure wave?

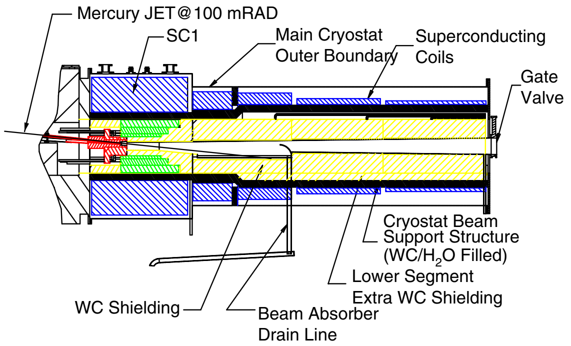

Fig. 3. Schematic view of a 4 MW target system with Mercury JET and 20 T solenoid.

In BNL E595, series experiments were carried out to study comprehensively on targetry and capture for neutrino factory/muon collider including above issues.

First studies on the interaction of a proton beam with a mercury target were performed with a 'trough' of mercury with proton beams at BNL and CERN/ISOLDE [4]. Subsequently, a free 1 cm diameter mercury jet was struck by 24 GeV proton pulse. Propagation of dispersal due to the beam-induced shock wave was successfully observed as shown in Fig. 4. These studies revealed that the speed of sound in mercury is reduced temporarily and that longitudinal propagation velocity is slow enough to protect the jet nozzle.

Studies on the interaction of a mercury jet with magnetic field were carried out at the Grenoble High Field Magnet Laboratory with a superconducting magnet. A 4 mm Mercury jet with 12 m/s velocity was injected into high field up to 20 T (Fig. 5). It was confirmed that the mercury jet can be injected into the magnetic field with 0 and 100 mrad to the magnetic axis. Stabilization of surface perturbations were observed, which is caused by the magnetic pressure on the conductor.

Simulation studies on the beam–jet interaction has been carried out. Preliminary results using FronTier code well-reproduced the above experimental results [6]. Simulation works which include the magnetic field are now in progress, suggesting that magnetic pressure of eddy current would suppress the dispersal of the jet. Fig. 6 shows FronTier simulations of a mercury jet in various strength of magnetic field. These results strongly motivate us to test experimentally the beam–jet-magnet interaction as introduced in the next section.

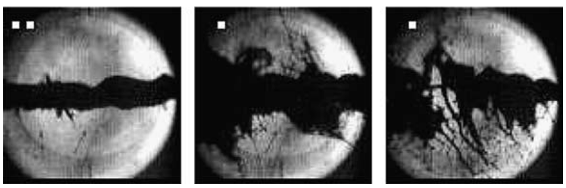

Fig. 4. Photographs of a 1 cm mercury jet struck by a pulse of 2×10^{12} 24 GeV protons [5].

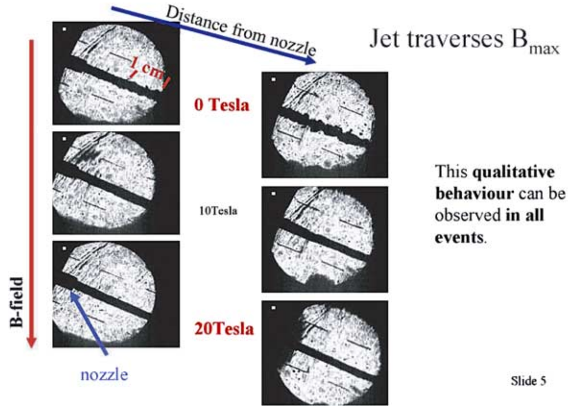

Fig. 5. Photographs of a 4 mm mercury jet with 12 m/s velocity in magnetic field of 0, 10, and 20 T [4].

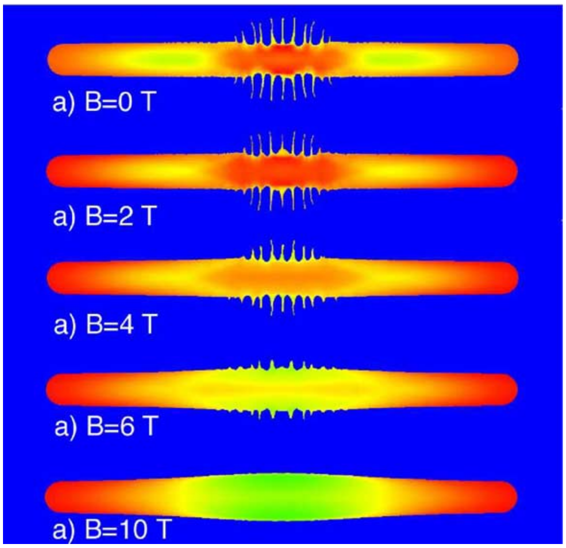

Fig. 6. FronTier simulation of a mercury jet in various strength of magnetic field.

2.2. Material studies for solid targets and windows

Solid stationary/moving targets are expected to survive with up to ~1 MW beam power, though it is still marginal. Even in case of a free mercury jet, beam windows are still necessary to isolate mercury from vacuum system. Material studies is inevitable to check feasibility of targetry system.

During BNL E951, various candidates of material for targets and windows were tested with 24 GeV proton beam and with fiberoptic strain sensors [7]. Thermo-mechanical response of carbon–carbon composite with 24 GeV proton beam was compared with that of typical graphite (ATJ). It is clearly seen from Fig. 7 that carbon–carbon composite is largely immune to beam-induced pressure wave thanks to its smaller thermal expansion. The question remains; whether this characteristic survives or not after irradiation?

Intensive searches were done for new materials adequate for targets in terms of the following properties:

1. small coefficient of thermal expansion (CTE),
2. high strength.

SuperInvar, INCONEL, and VASCOMAX were evaluated [8]. SuperInvar has nearly zero coefficient for thermal expansion (CTE) below 150 °C. However irradiation test using BNL-BLIP facility discouragingly revealed that CTE rapidly increased after small irradiation [9] as shown in Fig. 8. For other materials, properties change due to irradiation should be carefully checked. Further searches and irradiation tests are needed.

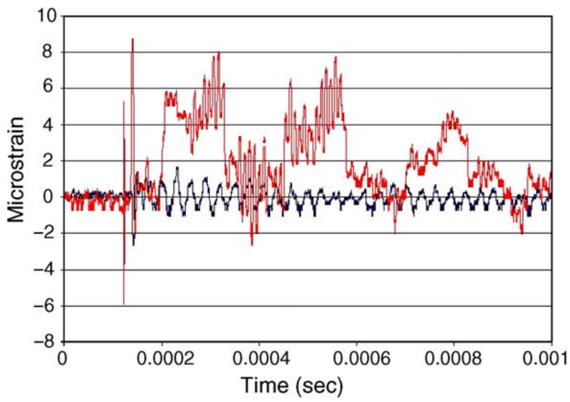

Fig. 7. Thermo-mechanical response of carbon–carbon composite and ATJ graphite.

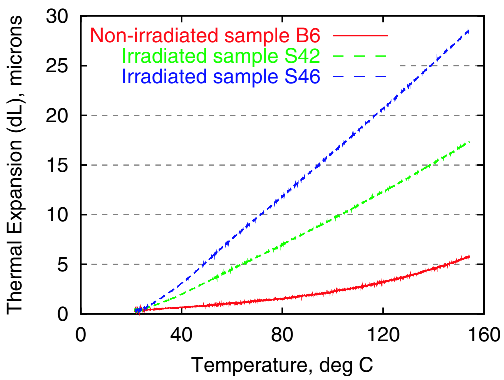

Fig. 8. Degradation of superinvar properties due to irradiation.

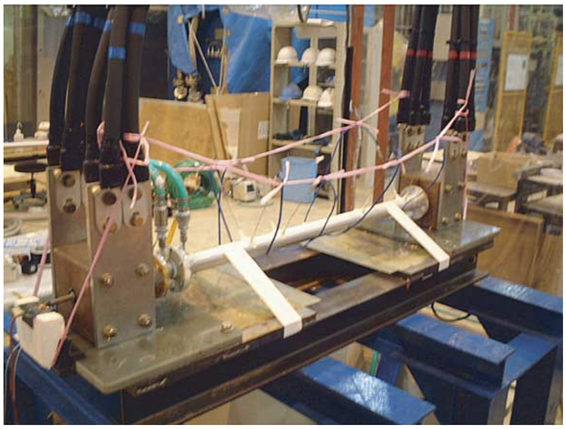

Fig. 9. R&D water-cooled graphite rod target for the J-PARC Neutrino experiment.

A water-cooled graphite rod is considered as a candidate of target for J-PARC 0.75 MW beam. The bench test shows a water-cooled system successfully removes heat of 20 kW (Fig. 9). Degradation material properties due to radiation is a next concern. IG43 graphite samples will be tested by irradiating in BNL-BLIP facility as describe below.

2.3. Pion collectors – capture and focus devices

Devices for collecting pions should be placed just outside targets and are exposed by extremely high radiation. Thus main issues on collectors are radiation damage of material and heat load from secondary particles. The latter is more serious in case for using superconducting solenoids. Heat load is estimated by using simulation code, e.g. MARS, MCNPX, etc., though there are very few validation data with high energy proton beam. Evaluation of these calculation, i.e., direct measurements of heat load from secondary radiation is crucial.

Also mentioned is a conducting pulsed target, which employs a new concept of combined function of both target and collector. Current status of a R&D program is briefly described.

2.3.1. Direct measurement of heat flux from targets

Direct measurement of heat load from targets was carried out with a dummy superconducting coil at KEK 12 GeV PS (Fig. 10). Proton beams are bombarded to the target with 20% interaction-length thickness and secondary particles are injected to the coil dummy. To measure small heat flux of a few watt, a 'cryogenic calorimeter' [10] was employed as follows: the coil dummy is cooled with GM-cryocooler down

Fig. 10. Direct measurement of heat load in the KEK 12 GeV PS.

to 10 K through thermal conduction of alminum strip. The heat flux is obtained by measuring temperature difference between the dummy and the cold head of the cryocooler.

To study angular dependence of the heat flux, measurements were made at various target position. As shown in Fig. 11, the preliminary data shows good agreement with MARS calculation within 20%, although the measured data show little excesses over MARS calculations [10].

2.3.2. Conducting pulsed target

A Pulsed target is proposed by Autin et al. [11]. Principles are schematically shown in Fig. 12. By applying pulsed current to generate a toroidal field inside the conducting target, secondary produced pions are focused and confined inside the target and as a result bright beam with low emittance could be obtained. According to simulation study [11], the target with 1 MA current would produce more pions than produced in the 20 T

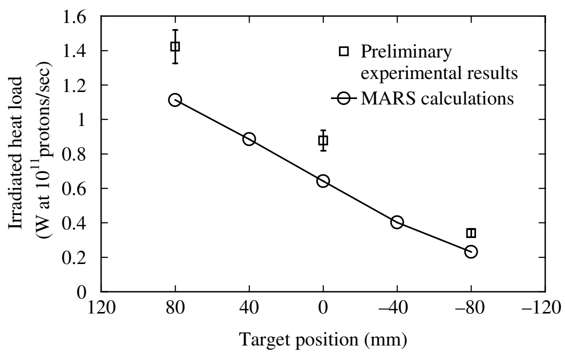

Fig. 11. Comparison between the preliminary measured heat flux and MARS calculations.

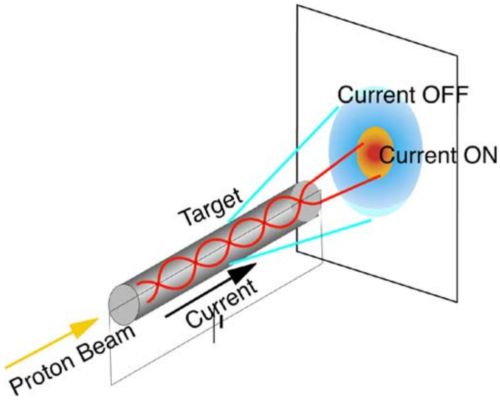

Fig. 12. Principle of a pulsed conducting target system.

solenoid. A strong advantage is that there is no need for superconducting devices under high radiation environment. There remain still many technical issues, e.g., strong electromagnetic force as well as shock wave from the impact of the beam, which may destroy target itself as well as containers or windows especially in case of mercury targets.

A prototype of the pulsed target is now being developed in KEK using mercury filled in the container. The pulsed current of 300 kA will be applied to see the electro-magnetic effect on the contained mercury and perform a proof of principle test using test beam.

3. Future R&D plans

3.1. Irradiation study of material

The first phase of irradiation test using BNL-BLIP facility has been successfully done as discussed. The second phase of experiments is now being prepared to test various spectrum of materials as follows [9]:

Carbon-carbon composite:

Whether favorable properties, small CTE and strength, are maintained after irradiation will be tested.

Graphite (IG43):

Isotropic graphite sample, IG43, is one of the candidates for the target material used in the J-PARC neutrino experiment. Change of volume size as well as mechanical properties will be measured.

Toyota GUM METAL:

Newly developed titanium alloy, 'GUM METAL', has a lot of superior properties, such as ultra-low elastic modulus, high strength, super elastic, and near-zero CTE, as shown in Fig. 13 [12]. The test will be made to check if these favorable properties survive after irradiation.

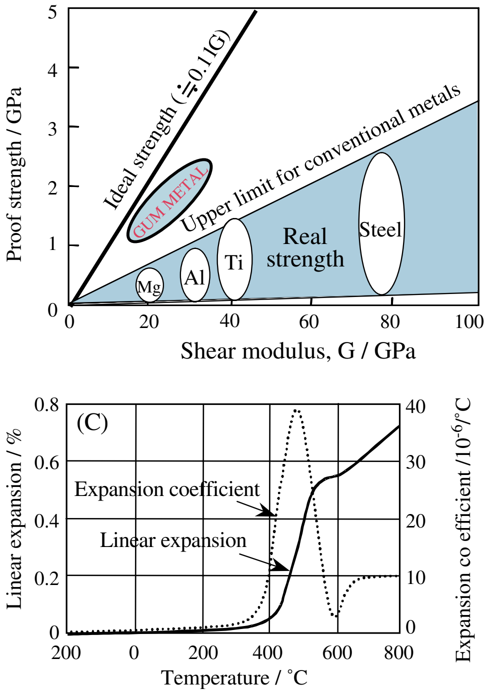

Fig. 13. Properties of GUM METAL [12].

3.1.1. VASCOMAX

VASCOMAX is an alloy which has about ten times tensile strength and fatigue limit as steel. Irradiation effect on CTE, fracture toughness and ductility loss are tested.

3.1.2. ALBEMET

ALBEMET, 62% berilium and 38% aluminum alloy, is a candidate material for a magnetic horn. Effect of irradiation on mechanical strength and CTE will be tested.

These material samples will be packed into baskets and irradiated in BNL-BLIP facility for two weeks. During irradiation, the baskets are cooled with water. Total radiation dose is estimated up to a few tenth of dpa. After cooled down for half a year, measurement will be performed in the remote handling hot cell facility as shown in Fig. 14.

3.2. Test with beam–jet-magnet at CERN

A beam test has been proposed to demonstrate a free mercury jet target system with both magnetic field and a beam [13]. The proposed area is in the TT2A tunnel of the NTOF proton line at CERN. A LN_2 cooled copper magnet was developed to produce 15 T field as shown in Fig. 15. The proton beam, with 4×10^{12} proton/s, will be used to study dispersal of the mercury jet due to both pressure wave and vaporization, and its magnetic suppression.

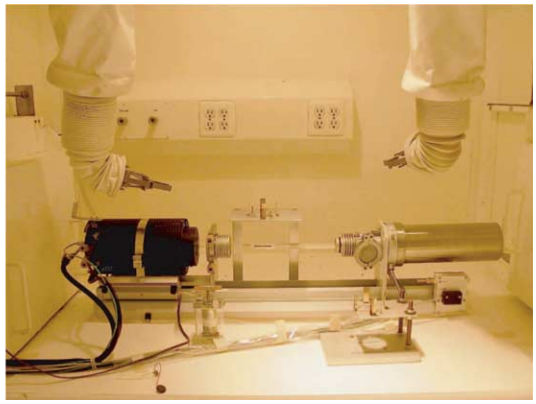

Fig. 14. CTE measurement of samples with remote handling system in the hot cell.

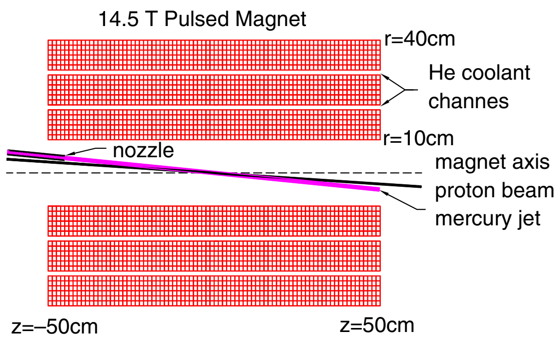

Fig. 15. Proposed setup with 15 T pulsed magnet and mercury jet.

3.3. Proof-of-principle test for 4 MW beam

A proof-of-principle test for 4 MW beam was proposed to J-PARC [14], which is now being constructed in JAERI at Tokai site, Japan (Fig. 16). The test will be performed with a pulsed proton beam, each pulse

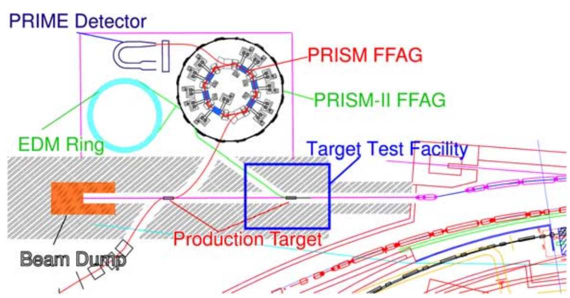

Fig. 16. Target test facility proposed at J-PARC.

of which contains 10^{14} protons. The studies will demonstrate feasibility of the target system against the issues of single proton pulses in case of 4 MW power.

4. Summary

Various R&D activities on target for neutrino factories have been proceeded. Most of them are carried out within international collaborations The recent results showed that a free mercury jet was demonstrated as a promising candidates for high power targetry. The next step is a feasibility test of beam–jet-magnet interaction, which is proposed to CERN and J-PARC.

The recent results of the material studies indicates that various new materials have attractive properties (such as small CTE and high strength) which could be used for the target with high power proton beam. Irradiation studies for these material have been carried out to check if their properties are maintained after irradiation and to test against long term radiation damage. For further studies, cooperation with other fields, such as neutron source, reactor, and etc. is crucial.

References

[1] BNL, in: S. Ozaki et al. (Eds.), Feasibility Study-II of a Muon-Based Neutrino Source, 2001.
[2] P. Gruber et al. (Eds.), CERN/PS/2002-080, CERN-NUFACT 122, 2002.
[3] NufactJ working group, A feasibility study of a neutrino factory in Japan, KEK Report 2003-5, 2003.
[4] A. Fabich, High power proton beam shocks and magnetohydrodynamics in a mercury jet target for a neutrino factory, PhD, Technischen Universitaat Wien.
[5] H.G. Kirk et al., Paper TPAH137 contributed to PAC2001.
[6] R. Samulyak, MUTAC Review Meeting, 15 January 2003.
[7] N. Simos et al., Thermal shock induced by a 24 GeV proton beam in the test windows of the muon collider experiment E951– test results and theoretical predictions, Contributed to AccAPP'01, 9 November 2001;
N. Simos et al., E951 Experiment target response re-evaluation, 10 May 2002;
N. Simos et al., Study of graphite targets interacting with the 24 GeV proton beam of the BNL muon target experiment, Contributed to EPAC 2002, 24 May 2002.
[8] P.A. Thieburger, H.G. Kirk, MUC-NOTE-TARGET-234.
[9] N. Simos et al., in: Proceedings of the 12th International Conference on Nuclear Engineering, Arlington, VA, 2004.
[10] H. Ohnishi et al., in: Proceedings of Nufact'03, New York, 2003.
[11] B. Autin, P. Thiebers, S. Gilardoni, Nucl. Instrum. and Meth. A 503 (2003) 348.
[12] K. Nishino, Toyota CRDL. Inc., Technical News, 21 April 2003;
T. Saito et al., Science 300 (2003) 464.
[13] J.R.J. Benett et al., A letter of intent to the ISOLDE and neutron time-of-flight experiments comittee, CERN-INTC-2003-033, 2003.
[14] S. Kahn et al., A letter of intent to the J-PARC 50 GeV proton synchrotron experiments, 2003.