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Progress in Absorber R&D for Muon Cooling ⋆

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Abstract

A stored-muon-beam neutrino factory may require transverse ionization cooling of the muon beam. We describe recent progress in research and development on energy

absorbers for muon-beam cooling carried out by a collaboration of university and laboratory groups.

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1 Introduction

To achieve the small emittance typically required for beam acceleration, a stored-muon-beam neutrino factory may require transverse ionization cooling of the muon beam [1,2]. [1] Such cooling can be accomplished by passing the beam through energy-absorbing material and accelerating structures, both embedded within a focusing magnetic lattice; the rate of change $d\epsilon_n/ds$ of normalized transverse emittance with path length is then given approximately by [3,4]

$$\frac{d\epsilon_n}{ds} = -\frac{1}{(v/c)^2}\frac{dE_\mu}{ds}\,\frac{\epsilon_n}{E_\mu} + \frac{1}{(v/c)^3}\frac{\beta(0.014)^2}{2E_\mu m_\mu\, L_R}, \tag{1}$$

where muon energy E_μ is in GeV, β is the transverse amplitude function of the lattice evaluated at the location of the absorber, and L_R is the radiation length of the absorber medium.

Simulations show that enough transverse cooling can be achieved to build a high-performance neutrino factory [2,5]. For example, neglecting Coulomb scattering (*i.e.*, ignoring the last term in Eq. 1), for typical parameter values (*e.g.* $\epsilon_n \approx 10\,$mm·rad and 200 MeV/c muon momentum) and a 10–15% packing fraction of absorber within the cooling channel, the cooling rate of Eq. 1 implies transverse emittance reduction by a factor $1/e$ in $\approx 50\,$m, about 3% of the muon decay length. In practice, with $\beta \approx 20 - 50\,$cm, one does a factor ≈ 2 worse than this because of scattering and other effects [2].

To minimize the effects of Coulomb scattering of the muons as they pass through the absorber, it has been proposed to use liquid hydrogen (LH_2) as the energy-absorbing medium [6]. Key issues in absorber R&D include coping with the large heat deposition by the intense ($\sim 10^{14}$/s) muon beam [2] and minimizing scattering in the absorber-vessel windows. Specifications of absorbers for some representative cases are given in Table 1. Our absorber-

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[1] Alternative designs without cooling have also been proposed [9].

[2] Palmer has suggested [10] that muon intensities an order of magnitude higher than this can be achieved, compounding the engineering challenge.

Table 1
Specifications of typical LH_2 absorbers (from the "Neutrino Factory Feasibility Study II" report [2]).

Absorber	Length (cm)	Radius (cm)	Number needed	Power (kW)	Window thickness (μm)
Minicooling	175	30	2	≈5.5	
SFOFO 1	35	18	16	≈0.3	360*
SFOFO 2	21	11	36	≈0.1	220*

* Design parameter for 1.2-atm maximum pressure

window R&D program is discussed in [7] and [8]. Here we give an overview of absorber R&D and a summary of recent progress.

2 Absorber development

The heat deposited in the hydrogen by the muon beam can exceed 100 watts per absorber (Table 1). LH_2 targets using an external cooling loop [11] have been successfully operated in such a heat-deposition regime [12], but engineering the fluid flow is a challenge [8,13]. We are developing prototypes using two design approaches [8]: a conventional, "flow-through" (cooling-loop) design, and a new approach using internal heat exchange, in which driven convection provides mixing and transverse flow [14].

Fig. 1 shows the mechanical layout of a flow-through absorber. Internal nozzles will be used to direct the fluid flow within the absorber to ensure adequate circulation and avoid dead zones or eddies. A room-temperature model with transparent plastic windows is under construction and will be used for first tests of the nozzle configuration using warm and cold water.

A critical-path item in absorber development is certification of safety by a Fermilab review committee. The stringent standards that must be met have been codified in [15] and include destructive testing of five windows of a given design before a sixth may be put into service. Pressure testing of a prototype window is underway [7].

3 Minicooling absorbers

As shown in Table 1, the Feasibilty Study II (FS2) neutrino factory design [2] includes two large "minicooling" absorbers. Their function is to lower the

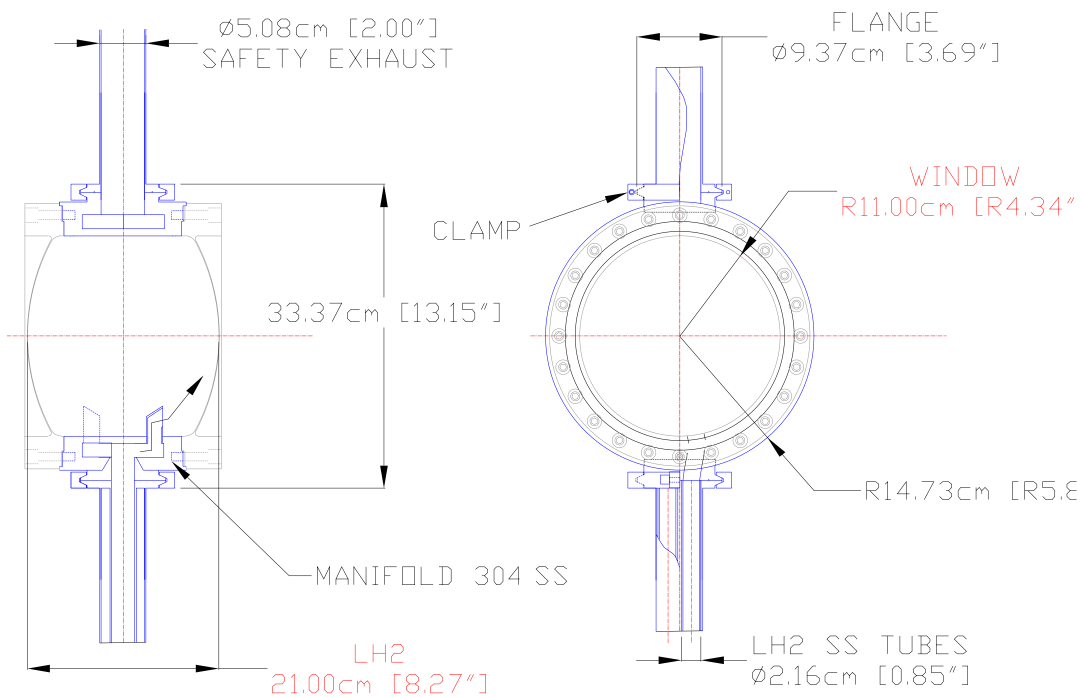

Fig. 1. Mechanical design of "SFOFO 2" absorber (flow-through version).

muon energy from the optimal energy for capture by the channel's focusing optics to that which is considered optimal for cooling.[3] At the same time they cool the normalized transverse emittance by $\approx \sqrt{2}$.

In the FS2 design it is assumed that the minicooling absorbers are composed of LH_2. Such large LH_2 tanks with such high power dissipation go considerably beyond LH_2-target experience. However, the parameters are not dissimilar to those of the Fermilab 15-foot bubble chamber [16].

While LH_2 minicooling is surely technically feasible, we have argued [2] that it is not necessarily the best choice. Minicooling via *e.g.* solid lithium or beryllium or liquid methane would also be feasible and might well be preferable from an operational standpoint. The additional multiple scattering entailed with a higher-Z absorbing material could decrease the flux out of the neutrino factory. H. Kirk has simulated this effect and has found the decrease to be only 5% for lithium and 10% for beryllium [2]. In principle this can easily be offset by raising the solenoidal focusing field slightly, however, detailed design studies of this idea remain to be carried out.

[3] Whether these energies are in fact the optima has not yet been definitively established, but they are the "provisional" optima assumed for the FS2 design.

Table 2
Linac-area test facility beam specifications.

Parameter	Minimum	Maximum
Beam Size ($\pm 3\sigma$) at D.U.T.* (cm)	1	30
Beam Divergence† ($\pm 3\sigma$) at D.U.T.* (mr)	± 0.5	± 14
Number of Pulses per Second		15
Number of Protons per Pulse (10^{12})	1.6	16
Pulse Duration (μs)	5.0	50

* D.U.T. = Device Under Test
† Min. divergence at max. size and vice versa.

4 Linac-area test facility

To support absorber tests, a new experimental area is under construction at Fermilab. Its location near the end of the Linac makes available 201- and 805-MHz power for high-power RF-cavity tests as well as 400-MeV H^- beam at high intensity. Table 2 gives specifications of the beam. Our planned program includes absorber bench tests and high-power 201-MHz RF-cavity tests followed by assembly of an integrated prototype cooling cell (including superconducting solenoids) for testing under radiation conditions typical for a neutrino factory cooling channel. More generally, the Linac-area test facility is a new experimental area at Fermilab available for any proposed experiment or test that calls for 400-MeV H^- or proton beam.

5 Gaseous absorbers

A new idea has started to receive serious consideration: use of high-pressure gaseous (rather than liquid) hydrogen as the energy-absorbing medium. If the gas is allowed to fill the entire cooling channel instead of being confined to roughly 10% of the channel length (as in current designs), matching the energy loss to the RF accelerating gradient requires a factor $\sim 10^2$ in density compared to that at STP. The pressure needed, especially if the hydrogen is cooled to liquid-nitrogen temperature, is then comparable to what has been used in the past for gaseous Cherenkov counters: about 20 atm.

Upon first consideration such an approach would appear to have significant drawbacks. These include the need for thick windows to withstand the pressure as well as the introduction of material inside the RF cavities, which could cause breakdown and (from Eq. 1) degrade the cooling rate (via multiple scattering at high-beta points of the lattice). However, calculations [17] show that the cooling performance can in fact be *enhanced* by use of gaseous absorbers: the many thin windows used in the LH_2 case are replaced by only two thick windows, which degrade the final emittance negligibly, and the dense gas inside the cavities in fact *suppresses* breakdown [18]. The recent development of cooling lattices with constant β [19] alleviates the last of the drawbacks. Further potential advantages include a more adiabatic cooling process, in which the energy loss and acceleration occur continuously and muon momentum swings are reduced, a slightly shorter overall channel length, which reduces muon decay losses, and improvement of RF efficiency via the decrease of cavity resistivity at low temperature.

A number of questions remain, including whether Paschen's Law (for high-voltage breakdown) is applicable in this regime of frequency, gas density, and radiation level, whether LN_2-temperature operation of 201-MHz RF cavities is indeed more economical when refrigeration costs are factored in, whether RF couplers can be designed to withstand 20-atm differential pressure, and whether constant-β cooling channels (even with gaseous absorber) are cost-effective compared to other proposed approaches. These will be subjects of R&D in the coming year.

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