Target System Concept for a Muon Collider/Neutrino Factory

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(May 28, 2014)
Specifications from the Muon Accelerator Staging Scenario

- 6.75 GeV (kinetic energy) proton beam with 3 ns (rms) pulse.

- 1 MW initial beam power, upgradable to 2 MW (perhaps even to 4 MW).

- 60 Hz initial rep rate for Neutrino Factory; 15 Hz rep rate for later Muon Collider.

- The goal is to deliver a maximum number of soft muons, \( \sim 40 < \text{KE} < \sim 180 \text{ MeV} \).
**Target System Concept**

- Graphite target ($\rho \sim 1.8 \text{ g/cm}^3$), radiation cooled (with option for convection cooling); liquid metal jet as option for 2-4 MW beam power.

- Target inside high-field solenoid magnet (20 T) that collects both $\mu^\pm$.

- Target and proton beam tilted with respect to magnetic axis.

- Superconducting magnet coils shielded by He-gas-cooled W beads.

- Proton beam dump via a graphite rod just downstream of the target.

- Some of the proton and $\pi/\mu$ transport near the target is in air.
Stainless-steel target vessel (double-walled with intramural He-gas flow for cooling) with graphite target and beam dump, and downstream Be window. This vessel would be replaced every few months at 1 MW beam power.

Proton beam tube
Last Final-Focus quad
Upstream proton beam window

15 T superconducting coil outsert, Stored energy ~ 3 GJ, ~ 100 tons

5 T copper-coil insert. Water-cooled, MgO insulated

He-gas cooled W-bead shielding (~ 100 tons)
Target System Optimization

- Graph 1: Yield per proton per GeV vs. Target length on solenoid axis, cm.
- Graph 2: Yield vs. Target Radius, cm.
- Graph 3: Yield vs. Beam Angle, mrad.
- Graph 4: Experimental data for Bz values of 20-2.5T and 15-2.5T.
Target System Optimizations

• **High-Z** favored.

• **Optima for graphite target:** length = 80 cm,  
  radius ~ 8 mm (with \( \sigma_r = 2 \) mm (rms) beam radius),  
  tilt angle = 65 mrad,  
  nominal geometric rms emittance \( \epsilon_\perp = 5 \) µm.  
  \( \beta^* = \frac{\sigma_r^2}{\epsilon_\perp} = 0.8 \) m.

• **Graphite proton beam dump:** 120 cm long, 24 mm radius to  
  intercept most of the (diverging) unscattered proton beam.

• The 20 T field on target should drop to the ~ 2 T field in the rest  
  of the Front End over ~ 5 m.
Issues for Further Study

• Thermal “shock” of the short proton pulse
  Probably OK for 2 MW and 60 Hz operation;
  15-Hz option needs study.

• Cooling of target, and the W beads.

• Lifetime of target against radiation damage.

• Beam windows.

• $\beta^*$ and beam emittance at the target.

• To preserve liquid-metal-jet upgrade option, need related infrastructure installed at $t = 0$. 
Thermal Issues for Solid Targets

When beam pulse length $t$ is less than target radius $r$ divided by speed of sound $v_{\text{sound}}$, beam-induced pressure waves (thermal shock) are a major issue.

Simple model: if $U =$ beam energy deposition in, say, Joules/g, then the instantaneous temperature rise $\Delta T$ is given by $\Delta T = U/C$, where $C =$ heat capacity in Joules/g/K.

The temperature rise leads to a strain $\Delta r/r$ given by $\Delta r/r = a \Delta T = a U/C$, where $a =$ thermal expansion coefficient.

The strain leads to a stress $P (= \text{force/area})$ given by $P = E \Delta r/r = E a U/C$, where $E =$ modulus of elasticity.

In many metals, the tensile strength obeys $P \approx 0.002 E$, $a \approx 10^{-5}$, and $C \approx 0.3 \text{ J/g/K}$, in which case $U_{\text{max}} \approx P C / E a \approx 0.002 \cdot 0.3 / 10^{-5} \approx 60 \text{ J/g}$.

Graphite @ 1400° C: $P = 42.4 \text{ Mpa}$, $E = 7.2 \text{ Gpa}$, $a = 4.8 \times 10^{-5}$, $C = 1.4 \text{ J/g}$, $U_{\text{max}} \approx 1700 \text{ J/g}$.

($a \approx 1 \times 10^{-5}$ for carbon-carbon composite)

[A nickel target at FNAL has operated with $U_{\text{max}} \approx 1500 \text{ J/g}$.]

These arguments are from *A Short Course on Targetry, KTM, NuFact03 Summer Institute*
How Much Beam Power Can a Solid Target Stand?

What is the maximum beam power this material can withstand without cracking, for a 6.75-GeV beam at 15 Hz with area 0.1 cm²?

Ans: MARS15 indicates that the peak energy deposition in a “pencil” target is essentially just that of dE/dx, ⇒ 1.5 MeV/(g/cm²) for graphite.

Now, 1.5 MeV = 2.4 \times 10^{-13} \text{ J}, so 1500 J/g requires a proton beam intensity of \( (1500 \text{ J/g})/(2.4 \times 10^{-13} \text{ J cm}^2/\text{g}) \approx 6 \cdot 10^{15}/\text{cm}^2 \).

⇒ \( P_{\text{max}} \approx 15 \text{ Hz} \cdot 6.75 \cdot 10^9 \text{ eV} \cdot (1.6 \cdot 10^{-19} \text{ J/eV}) \cdot (6 \cdot 10^{15} /\text{cm}^2) \cdot 0.1 \text{ cm}^2 \approx 1 \cdot 10^7 \text{ J/s} = 10 \text{ MW}. \)

If graphite cracks under singles pulses of > 1500 J/g, then safe up to 10 MW beam power @ 15 Hz.