MECO Production Target Developments

James L. Popp
University of California, Irvine

NuFact’03
Columbia, June, 2003
MECO Collaboration

Boston University
  J. Miller, B. L. Roberts, O. Rind

Brookhaven National Laboratory
  K. Brown, M. Brennan, L. Jia, W. Marciano, W. Morse, Y. Semertzidis, P. Yamin

University of California, Irvine
  M. Hebert, T. J. Liu, W. Molzon, J. Popp, V. Tumakov

University of Houston
  E. V. Hungerford, K. A. Lan, L. S. Pinsky, J. Wilson

University of Massachusetts, Amherst
  K. Kumar

Institute for Nuclear Research, Moscow
  V. M. Lobashev, V. Matushka

New York University
  R. M. Djilkibaev, A. Mincer, P. Nemethy, J. Sculli, A.N. Toropin

Osaka University
  M. Aoki, Y. Kuno, A. Sato

University of Pennsylvania
  W. Wales

Syracuse University
  R. Holmes, P. Souder

College of William and Mary
  M. Eckhause, J. Kane, R. Welsh
MECO Muon Beam Line at AGS

- **Goal:** $10^{11}$ stopped $\mu^-$ / sec
  - 1000-fold increase in $\mu$ beam intensity over existing facilities

- High-intensity proton beam and high-density target
- Target, cooling, & support: compact to minimize $\pi$ absorption
- Axially-graded 5 T solenoid field very effective at $\pi$ collection
Target Heating

- Target: High density cylinder, L = 16 cm, R = 3-4 mm
- $4.0 \times 10^{13}$ 7.5 GeV protons / sec from AGS
- Slow extraction, 0.5 s spill, 1.0 s AGS cycle time
- 2 RF buckets filled: 30 ns pulses, 1350 ns apart
- Total on-spill power deposition: 7500 - 9500 W
- On-peak energy deposition distribution:

![Graph showing energy deposition distribution](image.png)

V. Tumakov
Production Target Cooling

• Radiation
  – minimal material in production region to reabsorb π’s
  – significant engineering difficulties to overcome
    • high operating temperature, $T_{\text{operation}} = 2145 – 3000 \, \text{K}$
      - high thermal stresses
      - target evaporation
      - little hope of raising production rate beyond current goals
    • low-density materials: manageable stresses; but extended complex shapes, difficult to support & can lead to excessive pion reabsorption

• Forced Convection w/ water as coolant
  – low operating temperature, $T_{\text{operation}} < T_{\text{boil - water}}$
    - negligible thermal stresses
    - hope for achieving greater sensitivity
  – minor impact on MECO sensitivity: cooling system absorbs π’s
  – modest engineering difficulties handling coolant (water activation)
### Production Target Physics Simulations

Simulations of design parameters with GEANT3 indicate that both production target cooling methods can meet MECO physics requirements.

#### GEANT Simulations of Muon Yield

<table>
<thead>
<tr>
<th>Water Thickness (mm)</th>
<th>Ti Wall Thickness (mm)</th>
<th>(\mu^-) Stops per Proton</th>
<th>Acceptance Loss (%) (+/- 1.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.0050</td>
<td>0.0</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>0.0048</td>
<td>4.6</td>
</tr>
<tr>
<td>0.25</td>
<td>0.15</td>
<td>0.0048</td>
<td>4.1</td>
</tr>
<tr>
<td>0.2</td>
<td>0.15</td>
<td>0.0049</td>
<td>2.7</td>
</tr>
<tr>
<td>0.3</td>
<td>0.15</td>
<td>0.0048</td>
<td>4.5</td>
</tr>
<tr>
<td>0.4</td>
<td>0.15</td>
<td>0.0047</td>
<td>5.8</td>
</tr>
<tr>
<td>0.5</td>
<td>0.15</td>
<td>0.0047</td>
<td>6.3</td>
</tr>
<tr>
<td>0.25</td>
<td>0.2</td>
<td>0.0048</td>
<td>4.5</td>
</tr>
<tr>
<td>0.25</td>
<td>0.3</td>
<td>0.0047</td>
<td>6.7</td>
</tr>
<tr>
<td>0.25</td>
<td>0.4</td>
<td>0.0047</td>
<td>6.0</td>
</tr>
<tr>
<td>0.25</td>
<td>0.5</td>
<td>0.0047</td>
<td>5.4</td>
</tr>
<tr>
<td>2.35</td>
<td>0.76</td>
<td>0.0037</td>
<td>27.0</td>
</tr>
<tr>
<td>0.5</td>
<td>0.3</td>
<td>0.0041</td>
<td>17.8</td>
</tr>
</tbody>
</table>

Small water channel & thin containment tube costs 5% muon yield.

Inlet & outlet pipes and target radius should be reoptimized.

UCI: A. Arjad, W. Molzon, M. Hebert, V. Tumakov, J. Popp

Tungsten target: \(R = 3\) mm, \(L = 16\) cm

Radiation-cooled: All with 3 mm OD inlet/outlet pipes

Large inlet/outlet
Radiation Cooling: Lumped Analysis of Heating Cycles

- Tungsten cylinder
- R = 4 mm
- L = 16 cm
- Long time limit:

\[ T(t) = \bar{T}_{\text{max}} + \delta h(t), \quad \bar{T}_{\text{max}} = 2825 \text{ K} \]

\[ f_{\text{duty}} P_{\text{peak}} \approx \sigma \varepsilon (\bar{T}_{\text{max}}) \left( \bar{T}_{\text{max}}^4 - T_{\text{ambient}}^4 \right) A \]

\[ \delta = \frac{P_{\text{peak}} f_{\text{duty}} (1 - f_{\text{duty}}) \tau}{2C'_p (\bar{T}_{\text{max}})} , \]

\[ \delta = 42 \text{ K} \]

\[ C'_p (T) = C_p (T) + T dC_p / dT \]

- W: \( T_{\text{melting}} = 3683 \text{ K} \)
Radiation Cooling: On-Spill Temperature & Von Mises Stress

- Tungsten cylinder, symmetry ¼
- L = 16.0 cm, R = 4 mm
- Power distribution: gaussian
- Thermal dependence: Properties W

<table>
<thead>
<tr>
<th>T(K)</th>
<th>300</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>κ (W/cm K)</td>
<td>1.60</td>
<td>1.40</td>
<td>1.25</td>
<td>1.10</td>
<td>1.01</td>
<td>0.90</td>
<td>0.85</td>
</tr>
<tr>
<td>c_p (J/g K)</td>
<td>0.1313</td>
<td>0.138</td>
<td>0.1465</td>
<td>0.157</td>
<td>0.1723</td>
<td>0.1946</td>
<td>0.2255</td>
</tr>
<tr>
<td>α (1/K)×10⁶</td>
<td>0</td>
<td>4.04</td>
<td>4.42</td>
<td>4.82</td>
<td>5.22</td>
<td>5.61</td>
<td>6.01</td>
</tr>
<tr>
<td>E (Mpa)</td>
<td>41</td>
<td>38</td>
<td>36</td>
<td>34</td>
<td>32</td>
<td>28</td>
<td>23</td>
</tr>
<tr>
<td>σ_{Yield} (Mpa)</td>
<td>1519</td>
<td>150</td>
<td>110</td>
<td>75</td>
<td>40</td>
<td>20</td>
<td>N/A</td>
</tr>
</tbody>
</table>

- Region of maximum Von Mises stress, σ_{Yield} = 20 Mpa or less
- Dividing up target into 0.1 cm slices, slotting ⊥ & || to axis, spacing by 0.8 cm gives stability, but target size is unacceptable
Current Water-Cooled Design

- Pt or Au cylinder: $L = 16.0 \text{ cm}$, $R = 3.0 \text{ mm}$
- Ti inlet & outlet pipes: 25 cm long, ID = 2.1 mm, OD = 3.2 mm
- Annular coolant channel: $h = 0.3 \text{ mm}$
- Tapered inlet end reduces pressure drop across target
- Water containment shell: 0.5 mm wall thickness
- In MECO:
Target Installed in Production Solenoid

- 0.5” service pipes
- Slot in heat shield:
  - guide
  - positioning
- Simple installation:
  - robotic manipulation
  - no rotations needed
  - total of 1 vertical & 2 horizontal translations required
- Opening in heat shield for beam entrance
- Target rotated slightly off-axis to be optimally oriented for the beam
Target Fully Installed: Cut-Away Wide View of Production Solenoid

- Target
- Beam entrance
- Solenoid coil packs

W.Molzon, J.Popp, M.Hebert, B.Christensen
Water Cooling: Lumped Analysis of Heating Cycles

- Simple calculations and hydo code indicate large heat transfer coefficient
- Characteristic response time is of order AGS cycle time
- Target may reach steady state T on each cycle
- Time-dependent turbulent hydrodynamic simulations required to fully characterize the time behavior and more precisely the maximum coolant temperatures: CFDesign – suitable computational tool
Turbulent Flow in Annular Water Channel

- **Worst case**: steady state, 9500 W
- **Inlet water conditions**
  - temperature = 20 °C
  - flow rate = 1.0 gpm
  - velocity = 10.6 m/s at inlet
- **Flow channel**
  - length = 16.0 cm
  - radius = 3.0 mm
  - gap = 0.3 mm

- **Design parameters**
  - target pressure drop = 127 psi
  - inlet pressure = 207 psi
  - outlet pressure = 80 psi
  - max. local water temp = 71 °C
  - max. target temp (Au) = 124 °C (core)
  - mean discharge temp = 56 °C
  - stopped muon yield > 95% of rad. cooled
Steady State Temperature Distribution
Water-cooled Target

- Diffusion dominated heat transfer layer: 10-20 µm
- Fully developed turbulence in about 7 gap thickness
- Re: 15000 - 30000
Heat transfer calculations for turbulent flow conditions demonstrate feasibility of the cooling scheme.

- Turbulence calculation
  - unstable flow
  - $\bar{v} = \langle \bar{v} \rangle + \delta \bar{v}$, $\langle \delta \bar{v} \rangle = 0$
  - local fluctuations
  - $\delta \bar{v}$, $\tau_{turbulence}$
  - solutions to N-S eqs
  - time averaged, $\Delta t$
  - $\tau_{turbulence} \ll \Delta t$
Target Cooling Test Stand Diagram

- Control: target geometry & flow rate
- Monitor: temperature & pressure:
  - target inlet & outlet
  - reservoir
  - target (not shown)
- Temperature probes:
  - thermistors
  - thermocouple
- Measurements of interest in heating tests:
  - power deposition in target
  - heat transfer coefficients
target heat exchanger
  - target surface temperature
  - response times for power cycling
Target Prototype Tests

Water cooling effectiveness is being demonstrated via prototypes

• Pressure drop vs. flow rate tests completed
• First induction heating test completed, next test June 2003

Comparison of Prototype Data with HD Simulations

Actual pressure drop is lower than simulations predict

UCI: J.Popp, B.Christensen, C.Chen, W.Molzon
Induction Heating

- Principle: Excite eddy currents which oppose changing magnetic flux, to obtain heating via $\langle \mathbf{J} \cdot \mathbf{E} \rangle$
- Apply AC current to coil wrapped around work piece (e.g., solid rod, billet,...):

$H_0 = \text{surface magnetic field intensity}$

$P_{\text{total}} / A_{\text{rod}} = \frac{\rho H_0^2}{2\delta} f(R_{\text{rod}} / \delta), \quad \delta = \sqrt{2\rho / \omega \mu}$

- Ameritherm, Inc.; http://www.ameritherm.com
- Induction Heat Treet, Co.; Huntington Beach, CA
  - 20 kW, 175 kHz
  - 30 kW, 10 kHz
- Example: Tensile test for metals at extreme temperatures
Measured Power Deposition

- Solid rod:
  - R = 3.0 mm, L = 16.0 cm
  - Carpenter Technologies: High Permeability Alloy 49, 50/50 Fe/Ni
- Measured power deposited:
  - reservoir temperature rise
  - (outlet – inlet) temperature
- Approximately same result: 1450 W
- 264 W per K / unit discharge (gpm)
- Increase power deposition:
  - more turns per meter
  (coil w/ two close-packed layers)
  - reduce OD water containment shell
  - consider using higher-power unit

- Induction coil:
  - 152 turns/m
  - L = 23.6 cm, R = 3.8 cm
  - copper tubing: OD = 0.635 cm
- Power supply
  - Lepel 20kW unit
  - f = 175 kHz
**Measured Target Surface Temperature**

- **Annular water gap, h = 0.4 mm**
- **Flow rate = 1.0 gpm**
- **ΔP = 125 psi**

Skin depth: \( \delta = 0.018 \text{ mm} \)
- \( f = 175 \text{ kHz} \)
- relative permeability \( \mu/\mu_0 = 2050 \)
- \( T_{\text{target probe}} \):  
  - probe radial position not critical  
  - \( T_{\text{core}} - T_{\text{surface}} << T_{\text{target probe}} \)

**Target - Inlet**

- Probe near max surface T position:  
  - 1.9 cm in from outlet end  
  - > 0.5 mm below surface
- \( T_{\text{target}} - T_{\text{inlet}} = 21.0 \text{ C} \)
- Scaled to MECO: \( P_{\text{MECO}} = 7500 \text{ W} \), \( (T_{\text{target}} - T_{\text{inlet}})P_{\text{MECO}}/P_{\text{test}} = 108 \text{ C} \)
- Good approx.: \( T_{\text{surface}} = T_{\text{inlet}} + 108 \text{ C} \)
- To maintain non-boiling condition  
  - raise outlet pressure  
  - chill inlet water  
  - increase discharge rate
What next?

- Opera calculations: redesign coil for greater power
  - two layers of coil windings
  - reduce OD of copper tubing, etc.
  - evaluate using 20 vs 30 kW unit (higher current & lower freq)
- 2nd heating test in June 2003
  - improved sensor operation
  - higher power deposition
  - gap size 0.4 mm, run at higher flow rate
  - gap size 0.3 mm, run at various flow rates
  - more precise positioning for target surface temperature probe
  - characterize response time of target
- Opera calculations: design coil for MECO longitudinal heating profile
- Redesign water containment shell to improve pressure drop
- More heating tests in July 2003